The Physics of Balloons and Their Feasibility as Exploration Vehicles on Mars

S. M. Greenfield and M. H. Davis

September 1963

R-421-JPL

A REPORT PREPARED FOR

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

The RAND Corporation

1700 MAIN ST. • SANTA MONICA • CALIFORNIA

This research was supported and monitored by the Jet Propulsion Laboratory, California Institute of Technology under Contract Nos. N-33561 and N-950505 (NAS7-100) for the National Aeronautics and Space Administration. This Report does not necessarily represent the views of the Jet Propulsion Laboratory or the National Aeronautics and Space Administration.

RAND PUBLICATION

R-421-JPL

THE PHYSICS OF BALLOONS AND THEIR FEASIBILITY AS EXPLORATION VEHICLES ON MARS

S. M. Greenfield and M. H. Davis

September 1963

in brief

This Report presents a development of balloon theory and an analysis of the performance of balloons as vehicles on Mars. The authors develop a general theory that describes the behavior of extensible balloons and three classes of nonextensible balloons. With reasonable assumptions concerning the Martian atmosphere and concerning the success of certain research efforts, the theory indicates that the tasks at which balloons can be useful and efficient on Mars are quite varied.

67 pp. incl. Illus.

The RAND Corporation
1700 MAIN ST. • SANTA MONICA • CALIFORNIA

571030 p84

N-950505 (NAS7-100)

The Physics of Balloons and Their Feasibility as Exploration Vehicles on Mars

S. M. Greenfield and M. H. Davis

September 1963

R-421-JPL

A REPORT PREPARED FOR

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

The RAND Corporation

1700 MAIN ST. • SANTA MONICA • CALIFORNIA

SUMMARY

The first planet that will be explored thoroughly will be Mars, and the first stage in such an exploration, after studies by fly-by and orbiting vehicles, will be to land an instrumented package on the surface. When the instruments have measured what they can in the landing location, further information about the surface of the planet and its atmosphere can only be gained by lifting instruments into the atmosphere and moving instrumented packages from one point on the surface to another. Balloons appear to offer many special advantages for both of these tasks. They are conceptually simple, can be made very reliable and, once aloft, are driven by the winds with no fuel expenditure.

Balloons are more versatile than is generally supposed. Extensible balloons, such as those used for radiosondes on Earth, should be effective high-altitude probes of the Martian atmosphere. The recently developed superpressure balloon, using nonextensible fabrics such as DuPont's Mylar, can support an instrument package aloft for days without using ballast; the potential value of such a system to carry instruments for the study of Mars' surface while drifting with the winds is obvious. Another important use of the balloon on Mars will be to transport relatively heavy loads over short distances.

Existing balloon "theory" was developed largely on the basis of practical experience. To analyze the possibilities of balloon operations on Mars, a coherent theory of balloon flight was developed and is presented in this Report. The theory is applied to the major classes of balloon — extensible, superpressure, equal-pressure, and hot-air — and formulas are derived by which their performance in the atmosphere of any planet can be analyzed. A summary of present knowledge of the atmosphere of Mars is presented, and numerical examples are given for balloon performance on Mars.

A problem of great importance is the question of buoyant gas and how to transport it from Earth. The analysis presented in this Report does not completely solve the problem, but it leads to the conclusion that hydrogen is the best gas to use. Three methods of transportation are discussed: as a gas under high pressure, as a cryogenic liquid, and bound in chemical compounds. The most convenient of these, and also in some ways the most problematical, is the last.

Another element of the balloon system that is given an extended treatment is the fabric. It may be that neither rubber nor neoprene, the two fabrics currently used for extensible balloons, will be suitable for Mars because of their vulnerability to the anticipated low temperatures and high ultraviolet-radiation fluxes. Mylar appears to be a suitable choice for the superpressure balloon, although it may be difficult to sterilize adequately. The factors that must be taken into consideration in the choice of fabric are outlined, and new fabrics that might offer advantages are discussed.

Any space-borne system must be designed to be reliable, to occupy a minimum volume aboard the spacecraft, and to be as light in weight as possible. These desiderata are repeatedly stressed in the Report. Reliability is not readily quantified at this stage, but the other criteria, weight efficiency and volumetric efficiency, are presented as the quantitative bases for selecting a system. Insofar as possible, complete systems are described to illustrate the various uses of balloons in Mars' atmosphere. The numerical conclusions are tentative for several reasons: the analysis is incomplete; many parts of the total balloon system were hypothesized on the assumption that research would turn up the answers; and the properties of Mars' atmosphere are somewhat uncertain. However, under stated assumptions, it appears that an expenditure of less than 100 kg would permit ten identical extensible balloons carrying 1 kg each to be sent to useful altitudes to study the atmosphere, or would permit a 10-kg package to be carried an indefinite number of days by superpressure balloon. These are typical results.

Although the use of balloons to aid in exploring Mars appears feasible and highly advantageous, many questions remain to be answered. A number of suggestions are given to indicate the direction that research should take if this idea is to be made into a workable system. Since many of the theoretical results apply to balloons generally, they will be of interest not only to space scientists, but to terrestrial meteorologists and geophysicists as well.

Appendixes in the Report deal with important specialized problems: balloon temperature, methods for gas transport from Earth, and the dynamics of the rising balloon.

CONTENTS

I. INTRODUCTION — THE CASE FOR BALLOONS ON MARS

The series of exploratory missions that the United States proposes to launch to Mars consists, initially, of a simple probe passage of the planet and, ultimately, of a manned expedition to explore the surface. Between these extremes, but early in the series, various instrumented packages will be landed to telemeter whatever data can be obtained about the surface and about the atmosphere.

If Mars' surface is physiographically as varied as its mottled appearance suggests, surface measurements will be meaningful only when data have been accrued from an adequate sample of surface locations. Moreover, raw "geophysical" data will form a coherent picture of the atmosphere and its characteristics only when observations have been amply distributed in time as well as in space.

Several suggestions have been made for vehicles that can range the planet and explore it thoroughly and systematically. The suggested vehicles walk, crawl, roll, or hop over the surface and are visualized as being either remotely controlled or elaborately programmed to meet foreseeable contingencies. Regardless of the locomotive principle chosen, and even if they could be made reliable, such vehicles remain complex, energy-consuming mechanisms whose weight is prohibitive for early soft landings.

One vehicle that can lift an instrument payload and carry it a useful distance is the balloon. The only real disadvantage to balloon transport is that the balloon's course and speed are capricious and its travel time and distance are under only minimal control, for "the wind bloweth where it listeth." Consequently the balloon neither returns to base, nor is it recovered. But for early unmanned exploration of a planet, this is unimportant.

What is important is that balloons can lift efficiently. Balloons require no propulsive engine or fuel, because the winds* provide free motive power. They cross chasms and mountains without extra expenditure of energy. They provide an elevated observation point unattainable by any ground-based vehicle. They are relatively lightweight and inexpensive, and they can be made quite reliable. In the last decade, significant advances in the design and utility of free balloons have been brought about, primarily by the development of extruded plastic films of uniform quality, low porosity, and great strength. As a result of these advances, lightweight balloons are available that can carry relatively large loads and that can float near a predetermined level in the atmosphere for hours or even days.

Recognizing that one objective of exploration must be information of a quantity and quality that is meaningful, and recognizing that the payloads of early Martian landing capsules are severely limited, this report examines the capabilities and limitations of several balloon systems for Mars' exploration.

It turns out that the technical considerations bearing on the success or failure of the Mars balloon are of several kinds, and each must be examined in full knowledge of its penalty in payload and its effect on reliability. Primary among these considerations are (1) the several possible balloon types; (2) the type of gas used; (3) the means for storing a lifting gas for the interplanetary voyage; (4) the means for inflating the balloon; (5) the means for launching the balloon; and (6) the basic operational considerations for a balloon in a remote environment. These are considered, quantitatively where possible, otherwise qualitatively in the following chapters. Where quantitative results are unobtainable suggested areas of research are indicated.

---

*According to Mintz,[1.1] the wind regimes of Mars probably alternate with the season from hemisphere to hemisphere. Half the year in each hemisphere, the winds would be turbulent and unpredictable, with possible doldrums; in the other season, he believes, there would be steady easterlies and westerlies not unlike Earth's trade winds.

One question that is not considered quantitatively in this analysis is that of the compatibility and reliability of a balloon system. Uncertainties exist that permit only a preliminary qualitative discussion of these subjects. However, the final design of a balloon system must be based to no small extent on the compatibility of that system with other elements in the spacecraft and with the spacecraft experiments. Within the balloon system itself, of course, one must strive toward reducing the number of parts, eliminating moving parts, raising the reliability of all components, and keeping the system, as far as possible, free of dependence on outside systems. Reliability is probably the single most important attribute of a space system. Where possible in this report, we have attempted to keep both compatibility and reliability in mind when considering the various component parts of conceivable balloon systems.

REFERENCE FOR CHAPTER I

1.1 Mintz, Yale, "The General Circulation of Planetary Atmospheres," Appendix 8 in W. W. Kellogg and C. Sagan, The Atmospheres of Mars and Venus, National Academy of Sciences--National Research Council, Publication 944, Washington, D. C., 1961.

II. BALLOONS IN A PLANETARY ATMOSPHERE

Experimental Uses

In considering the usefulness of balloons for studying a planet, three modes in which such a vehicle can operate should be recognized. Each mode has its own utility. In the discussions in this report, a telemetry or communication link permitting the relay of information to Earth is assumed in all three modes, and this will remain an assumption here, as communication and telemetry lie outside the scope of this report.

The three modes of operation are:

(a) The balloon used as a sensor. (The desired data is obtained by tracking the balloon itself and recording the motion.)

(b) The balloon used as a platform. (The balloon supports instruments, which perform the measurements.)

(c) The balloon used as a conveyance. (The balloon moves an object from one point to another.)

Several possible experiments are listed below, arranged according to mode of operation.

THE BALLOON AS A SENSOR

Since a balloon that is neutrally buoyant in the atmosphere moves approximately with the air, its motion reveals the wind speed and direction at its floating altitude. Of course, if data are to be obtained, the balloon must be tracked; its position relative to some fixed position must be known as a function of time.

THE BALLOON AS A PLATFORM

The second mode of operation permits a broad choice of uses for a balloon on a remote planet. The balloon is a mobile platform. Any instrument small enough to be carried and reliable enough to be operated remotely is a candidate for use. A multitude of possibilities could be listed; no list would be exhaustive, but for illustration, a few specific examples can be cited.

The most familiar operation in this mode is the measurement of meteorological parameters. Using a single, extensible balloon that expands as it rises until it bursts, it is commonplace on Earth to send instruments aloft that measure pressure, temperature, radiant-heat flux, and other physical quantities as a function of altitude along a single, more-or-less vertical line. From such measurements can be derived the variation with altitude (over a single point) of such important parameters as density, water-vapor content, and radiation-flux divergence. On Mars, similar measurements would yield important information about the structure of the atmosphere, although the variation of many atmospheric parameters in space and time could not, of course, be predicted on the basis of one sounding (or even many soundings) over a single location.

However, a simple, single-point balloon ascent on Earth can provide many geophysical data beyond the usual meteorological measurements, and the same is true of Mars.

It may be objected that similar measurements can be made from the Mars capsule itself during its descent through the atmosphere; but the release subsequently of a vertical-rising balloon would give additional measurements at another selected time. Much valuable information would be obtained if a relatively large number of vertical ascents were made at various times and from dispersed locations.

Considerably more flexible in operation is a balloon that can float for a long period at a predetermined density level in the atmosphere. Such a vehicle becomes an observation platform of good stability that, depending on the winds, permits a variety — or even a great variety — of measurements to be made over a considerable distance and time.

From such a platform drifting across Mars, standard meteorological measurements could be made; the resulting data, when combined with measurements made by the capsule during entry, would begin to yield information on the structure and variability of the Martian atmosphere. To be sure, the balloon measurements would be made at a single density level in the atmosphere, or at most, at two or three levels, but these data could be supplemented by parachuting instruments in small packages from the "mother" balloon at regular intervals. Such a procedure would add another dimension to these data.

A platform suspended some distance below the balloon would permit instruments to look down or up at quite a large angular area of ground and sky. A radiation detector aimed downward could sense radiation emitted or reflected by ground, clouds, or haze. A more complex photographic or television camera could record surface-wind directions and speeds by observing dropped smoke bombs or flares, could scan surface features in detail, and could seek evidence of life. Data from infrared or microwave radiometers would permit estimation of the surface temperatures and the emissivities of relatively fine topographic features. A gamma-ray detector could provide evidence of the radioactivity of the surface.

A spectrometer and a polarimeter aimed upward at scattered visible sunlight would provide continuous data that, combined with knowledge of the look angle and the solar position, would provide information on scattering and polarization in the atmosphere, from which the nature of airborne particles might be inferred. Sensors could detect the presence of clouds and haze layers in the high atmosphere and thin horizontal distributions, either of which could then be studied more closely by other methods. Looking up in the ultraviolet absorption bands of ozone would lead to a determination of the vertical and the horizontal distribution of that gas.

A wind-carried platform would permit a wide variety of physical observations to be made at the floating level. The magnetic field could be monitored as the balloon drifts away from its launch point. Such data would be particularly useful if coupled with data from a continuously recording magnetometer at the home base. There are other important physical quantities that could be measured: cosmic rays, atmospheric electric fields and field gradients, and electrical disturbances arising from such an atmospheric phenomenon as a dust storm.

The search for life forms usually has the highest priority in a list of experiments for Mars. As a part of this search, samples taken at the floating altitude of the balloon might be analyzed for the presence of spores and bacteria. In addition to the photographic or television survey already mentioned, spectral measurements similar to those made by Sinton[2.1] might produce data on the presence and distribution of plant life.

THE BALLOON AS A CONVEYANCE

Used as a conveyance, a balloon can serve to move one or more devices, making it possible for (a) one package to operate successively at two or more locations, or (b) a number of devices to operate simultaneously at more than one location. By combining and pyramiding these two transportation functions, permutations can be evolved that are limited only by payload restrictions.

A balloon could be used to seed a number of similar experimental packages over a large area for simultaneous studies of selected parameters. For example, small, self-contained balloon launchers might be distributed that would simultaneously release balloons to probe the atmosphere vertically from different locations.

After the capsule has made its measurements at the landing location, it might also be desirable to move the entire instrument package to a new location having different environmental characteristics. The balloon would be launched and would rise to its floating altitude carrying the instrument package and noting the local albedo of the ground. It would continuously monitor the albedo of the planet's surface as it drifted with the wind at the equilibrium level. When the albedo was significantly different from the value at the original landing point it would descend. Obviously, any other measurable parameter could be used to trigger the descent of the balloon; the objective is for the balloon to descend where the "terrain" is different in kind, and repeat the measurements.

A variant on the operation just described would be to choose in advance two or more surface characteristics that would be of most interest. Then two or more balloon units would be included in the capsule.

Regardless of the chance environment at the landing point, the balloons would separately lift the units and would individually seek the two locations whose physical parameters corresponded to the preselected values (such as high and low surface radioactivity or temperature), at which places surface studies would be made.

As a final interesting case, the balloon might be used to separate interfering parts of the same payload or parts that must be separated for the payload to function properly. Sensitive electronic and radiation-measuring equipment, for example, could be separated from a nuclear reactor. Explosive charges could be "seeded" by a balloon at various distances from a seismometer.

Introductory Balloon Theory

The suggestion that balloons be used in exploring a planet may reasonably evoke the supposition that any such simple device, after two hundred years or more of use, must be thoroughly understood. However, when an attempt is made to optimize a balloon system for useful mass-carrying efficiency (i.e., minimizing the total load to be transported from the earth to the planet), or when balloon theory is studied in detail, the concept of a balloon as a simple device quickly disappears. Instead, the balloon emerges as a complicated thermodynamic and hydrodynamic system that makes it a difficult problem for the designer to find the best design.

It is not that there is a dearth of empirically derived techniques for lifting a payload and keeping it aloft. Such techniques have multiplied as experience has grown and technology advanced. Nor is it that basic balloon physics is particularly difficult. But serious problems arise when we try to predict all or nearly all of the pertinent parameters in order then to compute what minimum of effort, material, or expense is required to achieve a desired result.

In this section, then, to put the problem in proper perspective, and to introduce later, more specific considerations of balloon dynamics, the basic theory of balloons (i.e., why they rise and float) will be examined, and the forces that affect them will be indicated. There will be an attempt to show under what circumstances a balloon's gas temperature becomes important, and how reasonable approximations to the equations of motion might be obtained for a balloon rising in a still atmosphere in which the temperature varies adiabatically.

BUOYANCY AND LIFT

By Archimedes' principle,[2.2] the buoyant force, F_B, on a bubble of gas in the atmosphere is

$$F_B = \rho V g - mg, \tag{2.1}$$

where ρ is the air density, V is the volume of the bubble, g is the local acceleration of gravity, and m is the mass in the bubble. If

$F_B = 0$, the bubble is neutrally buoyant (i.e., floating, but not rising or falling). For the bubble to rise in the atmosphere, there must be a force imbalance, $F_B > 0$. However, if such an imbalance exists, and the bubble is therefore in motion, the retarding force due to the medium must be taken into account. The total force, F_T, on the bubble of gas, then, is given by

$$F_T = F_B - F_D = m^* a, \tag{2.2}$$

where F_D is the drag force; $m^* = m + \frac{1}{2}\rho V$, the "virtual mass" required by hydrodynamic theory;[2.3] and $\underline{a}$ is the acceleration upward.

If we encase the gas bubble within a balloon, m becomes

$$m = m_g + m_b + m_p \quad , \tag{2.3}$$

where m_b is the mass of the balloon fabric, and m_g is the mass of the balloon gas. For simplicity, the expression m_p, "payload plus fixed mass" will be defined to include all the mass lifted except the gas and the fabric. Further, it will be understood that V is the volume of the contained gas at any given altitude, and not necessarily the maximum volume the balloon may reach. The volume of the payload is neglected.

Let us write the perfect gas law in the form

$$pV = RT' m_g / M_g \quad ,$$

where M_g is the molecular weight of the balloon gas, T' the gas temperature, p is the pressure, and R is the gas constant. Then, assuming that the pressure inside the balloon is equal to the ambient air pressure, the mass of air displaced by a volume of gas V, becomes

$$\rho V = \frac{M_a}{M_g} \frac{T'}{T} m_g \quad , \tag{2.4}$$

where M_a is the molecular weight of the atmosphere, and T is the ambient temperature. In this equation and elsewhere in this report, unless otherwise stated, primed quantities refer to conditions inside the balloon; unprimed quantities refer to ambient atmospheric conditions.

For a nonextensible balloon (a nonstretching balloon having a fixed maximum volume, V_b), Eq. (2.4) holds as long as the volume of gas is less than V_b.

Once the volume of a nonextensible balloon equals its maximum value (V_b), the condition of neutral buoyancy ($F_B = 0$) is soon established, and the balloon is then floating at a constant-density "surface" in the atmosphere. The specifics of how a balloon achieves and maintains this condition of neutral buoyancy are a function of the type of nonextensible balloon and will be considered in detail in Chapter V.

For an extensible balloon, one that expands as it rises until it bursts, there is a factor affecting Eq. (2.4) if calculations are to be precise: because of the tension of the stretched material, a differential pressure must exist across the balloon fabric. Under these conditions, the rate of change of volume with altitude must reflect the change in this pressure differential. The error that enters the calculation of balloon volume when the pressure differential is neglected is proportional to the ratio of the pressure differential to the ambient pressure. On Earth, this ratio is small enough to be neglected except when extensible balloons are close to burst altitude. However, on Mars, a correction to Eq. (2.4) is required for extensible balloons. In Chapter V, the dynamics of the extensible balloon will be treated in more detail, taking differential-pressure effects into account, but we will assume that Eq. (2.4) is valid for the purposes of the present discussion.

The buoyant-force equation can now be written as

$$F_B = g[m_g(\beta - 1) - m_L] \ , \qquad (2.5)$$

where m_L is the load aloft ($m_L = m_p + m_b$), β is equal to the ratio of the density of the atmosphere near the balloon to the density of the contained gas:

$$\beta = \frac{\rho}{\rho'} = \frac{M_a}{M_g}\frac{T'}{T} \quad . \qquad (2.6)$$

It is interesting to note that Eq. (2.5) essentially says that, within the variation of β, the buoyant force on a balloon is constant with altitude. For neutral or positive buoyancy, $F_B \geq 0$, requiring that $\beta > 1$. This condition indicates that for a gas to lift a balloon it must have a molecular weight significantly less than the molecular weight of the ambient medium, or else must be at a significantly higher temperature than the medium. The hot-air balloon of old-time carnivals illustrates the latter condition; "hot-air" balloons for Mars are discussed in detail in Chapter V. Equation (2.5) illustrates that once a choice has been made of the gas for a balloon, its mass, the mass of the payload, and the size and material of the balloon, the buoyant force is determined completely by the ratio of the temperature of the gas to the ambient temperature. The performance of a balloon in a planetary atmosphere depends strongly on the ratio of internal to external temperature, a quantity that varies with altitude, location, time of day, balloon gas, and balloon material. It is obvious that any attempt to optimize a balloon system for Mars must take this temperature effect into account. Most of what is known quantitatively about this parameter has been determined empirically for balloons operating in our own atmosphere and does not carry over adequately to Mars. Appendix A attempts to treat the gas-temperature problem on Mars.

From Eq. (2.5) the mass of lifting gas required to produce neutral buoyancy, m_{go}, is

$$m_{go} = \frac{m_L}{\beta - 1} \quad . \tag{2.7}$$

The mass of gas required to produce a specified initial upward acceleration is given by

$$m_g = \frac{m_L}{\beta^* - 1} = m_{go}(1 + \epsilon_g) \quad , \tag{2.8}$$

where

$$\beta^* = \beta \, \frac{1-\lambda/2}{\lambda+1} \quad ,$$

λ is $\frac{a_0}{g}$, the ratio of the initial acceleration of the balloon to the local acceleration of gravity, and

$\epsilon_g m_{go}$ is the mass of the "excess gas" over that required to establish neutral buoyancy.

Hence

$$\epsilon_g = \frac{\beta - 1}{\beta^* - 1} - 1$$

$$\approx (3/2)\lambda\beta/(\beta - 1) \ ,$$

for small values of λ, since then $\beta^* \approx \beta\left(1 - \frac{3}{2}\lambda\right)$.

For $\lambda \ll 1$,

$$m_g \approx \left[1 + (3/2)\frac{\lambda\beta}{(\beta - 1)}\right]\frac{m_L}{(\beta - 1)} \quad . \tag{2.9}$$

The parameter λ, as will become apparent, is important in determining the detailed performance of a balloon. It is discussed in Appendix C. From the analysis contained in that appendix we shall adopt a value of $\lambda = 0.1$ in this report, whence

$$\beta^* = 0.86\beta \qquad (\lambda = 0.1) \ . \tag{2.10}$$

THE RATE OF RISE OF A BALLOON THROUGH THE ATMOSPHERE

In a complete treatment of the theory of balloons it is necessary to consider the question of how fast a balloon rises in the atmosphere. Utilizing Eq. (2.2), one arrives at a differential equation expressing the vertical motion of a balloon in an atmosphere at rest,

$$\frac{dv}{dt} = \frac{F_a}{m^*} - \frac{1}{2m^*}\rho C_D v^2 A \quad , \tag{2.11}$$

where C_D is the drag coefficient, and v is the balloon's vertical velocity.

In Appendix C, a solution is obtained for this equation that is applicable to the lower part of the atmosphere, where the temperature varies adiabatically. This solution indicates that the balloon starts with an initial acceleration a_0 (equal to F_B/m^*), but within a vertical distance of several hundred meters in the Martian atmosphere (i.e., a small fraction of a scale height) this acceleration decreases to a very small constant acceleration equal to approximately $10^{-3}a_0$. Since this constant acceleration is very small, the vertical velocity is very nearly constant, provided F_B remains constant. A good first-order approximation to the velocity of a balloon rising through the lower atmosphere is the terminal velocity arrived at by assuming a balance between the buoyant and drag forces,

$$v = \sqrt{2F_B/\rho C_D A} \quad . \tag{2.12}$$

GENERAL BALLOON-PERFORMANCE EQUATIONS, AND THE CONCEPT OF BALLOON-SYSTEM EFFICIENCY

Assuming a spherical shape for all types of balloons (radius r), a general equation of the following form can be written:

$$\frac{4}{3}\pi r^3 C_V - 4\pi r^2 C_A - m_P = 0. \tag{2.13}$$

It is derived from the equation (2.2) expressing the buoyant force on the balloon. It groups together all those terms that are proportional to the balloon's volume into the coefficient C_V, and all those terms that are proportional to the balloon's surface area into the coefficient C_A; C_V contains factors referring to the lifting gas, the density of the air at the floating or bursting altitude, etc.; C_A includes the mass per unit of the balloon fabric.

Because this equation is cubic in r, it is somewhat troublesome to work with, and since it occurs frequently, a general method was devised for its solution.

Define the parameter ζ:

$$\zeta = \frac{m_p}{m_p + 4\pi\, r^2 C_A} \quad . \tag{2.14}$$

Then, rearranging,

$$\zeta = 1 - \frac{4\pi r^2 C_A}{m_p + 4\pi\, r^2 C_A} \, . \tag{2.15}$$

Eq. (2.13) may be regrouped

$$(m_p + 4\pi r^2 C_A) = \frac{4}{3}\pi r^3 C_V. \tag{2.16}$$

Solving Eqs. (2.15) and (2.16) for r, we have

$$r = \frac{3C_A}{C_V(1-\zeta)} . \tag{2.17}$$

Note that $r(1-\zeta) = 3C_A/C_V$, and so is independent of m_p. This is the radius of a balloon that can just lift itself, with $m_p = 0$. We will refer to $[r(1-\zeta)]$ as the "reduced radius."
Finally, from Eqs. (2.15) and (2.17),

$$\mu m_p = \frac{\zeta}{(1-\zeta)^3} , \tag{2.18}$$

where

$$\mu = \frac{C_V^2}{36\pi C_A^3} . \tag{2.19}$$

In Fig. 1 is a plot of the equation, ζ versus μm_p. The quantities C_A and C_V of Eq. (2.13), and therefore the parameter μ defined by Eq. (2.19), take specific forms for each balloon type (see Chapter V). The procedure for analysis of a particular balloon is therefore first to calculate C_A and C_V following the equations given in Chapter V; next evaluate μ according to Eq. (2.19). Then from the product (μm_p) the parameter ζ is read from Fig. 1. The required balloon radius is then given by Eq. (2.17). The balloon's volume and surface area are also readily computed using the parameter ζ with C_A and C_V.

$$V_B = \frac{m_p}{C_V\zeta} , \quad A_B = \frac{m_p}{C_A}\left(\frac{1}{\zeta} - 1\right) . \tag{2.20}$$

The parameter ζ is closely related to the ratio of m_p, the payload mass, to m_L, the total mass lifted by the balloon (not including the

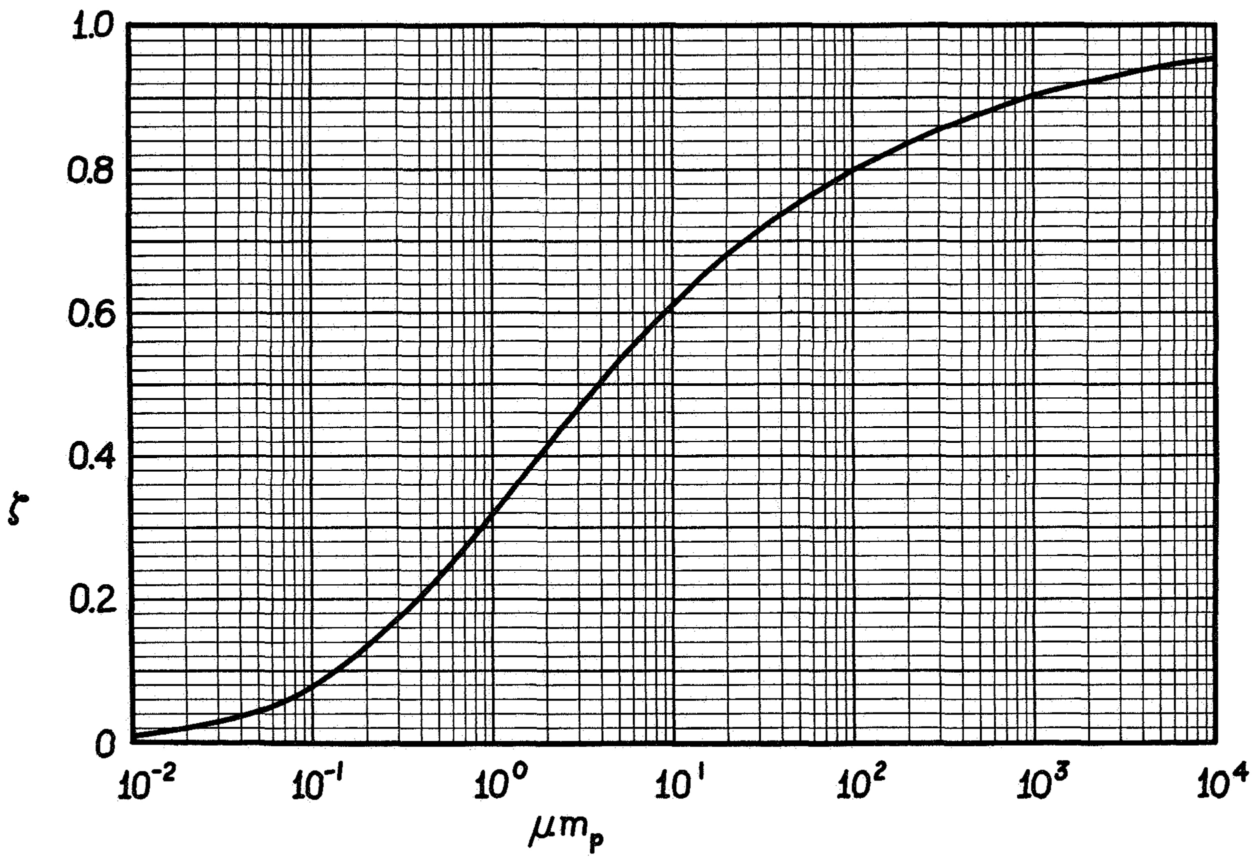

Fig. 1 — ζ versus μm_p, the "balloon analysis" curve

gas inside the balloon envelope). If $4\pi r^2 C_A = m_b$, the mass of the balloon fabric, then $\zeta = \frac{m_p}{m_L}$. This is the case for most of the balloon types analyzed here. But in general we can write

$$\frac{m_p}{m_L} = \zeta \left(\frac{m_p + 4\pi r^2 C_A}{m_L} \right) , \tag{2.21}$$

so the useful ratio m_p/m_L is readily derived from ζ.

As stated earlier, the "payload" m_p, as we use the term, consists of the complete package carried aloft by the balloon (but excluding the actual balloon weight). In addition to the instrument package, m_p also includes other equipment common to all balloons.* If we symbolize the <u>instrument</u> payload as m_p', then it may be related to m_p by an equation of the form $m_p = m_p' C_m + m_F$, where $(C_m m_p')$ includes those items that are proportional in mass to m_p', and m_F represents masses left over. This equation allows such ratios as m_p/m_L to be expressed in terms of m_p' rather than m_p if desired.

Since the ultimate aim of a balloon system is to lift a payload into the atmosphere, any evaluation of a balloon's performance must involve an estimate of its efficiency in accomplishing this task. We remarked that the parameter ζ, defined above, is closely related to the payload fraction of the total load lifted, m_p/m_L, which we call the "intrinsic efficiency" of a balloon. However, since this report is concerned with balloon operations on a distant planet, it is obvious that for comparison of total systems we must take into account the total mass and volume that must be transported from Earth. Accordingly, the ratios of most interest are the "total mass efficiency," m_p/m_T, and

*This common equipment includes a nylon load line whose strength is commensurate with the load to be carried, together with various hooks, fasteners, and linkages that permit the package to be attached to the line. In addition one might also include a parachute to lower the payload to the ground, and in the case of superpressure balloons, a simple diaphragm pressure-relief valve. In general, all of the additional equipment just enumerated does not amount to more than 10% of the total payload.

the "total volumetric efficiency," V_p/V_T. The quantities m_p, V_p are the mass and volume of the payload, while m_T and V_T are the mass and volume of the total balloon system loaded aboard the spacecraft at the time of launch (including the payload, the balloon, the gas, and gas-generation equipment, launching apparatus, etc.).

Usually the system of least mass is also the smallest, as measured by the ratio V_p/V_T, although not necessarily always. The total volume of the balloon system, V_T, is made up of the payload volume, V_p, the volume of the packed balloon, V_P, the volume of the gas-transport system, V_t, and the volume of auxiliary equipment — launching apparatus, brackets, housing, etc. For analysis, it will usually be necessary to adopt a nominal value for the mean payload density (1.0, for example) to relate V_p to m_p. The volume of the packed balloon, V_P is simply A_b/f_p, where A_b is the balloon's surface area, and f_P is the "packing fraction." The volume of the gas-transport system will be evaluated using the ratio V_t/m_g, which is computed for various gas-transport systems in Appendix B.

Besides the total efficiencies, a number of ratios are important in determining the balloon's performance. The lifting gas can be characterized by the ratio of the total mass aloft (excluding the gas), m_L, to the balloon's gross mass (i.e., m_L plus the mass of the gas). This ratio, m_L/m will be called the "lifting efficiency" of the gas.

The ratio m_p/m_L, the "intrinsic efficiency," has been previously described. Finally the gas-transport system, if a buoyant gas is used, has a mass efficiency (the "gas-transport efficiency") m_g/m_t, where m_t is the mass of the transport system including the gas actually used in filling the balloon (see Appendix B). All of these efficiency ratios necessarily lie in the range 0—1.

A summary of the efficiency ratios used in this report is presented in Table 1.

Table 1

EFFICIENCY RATIOS

Ratio	Meaning	Name
m_p/m_T	(payload mass)/(mass of total balloon system)	"total mass efficiency"
m_L/m	(mass carried aloft)/(gross mass—m_L+m_g)	"lifting efficiency of the gas"
m_p/m_L	(payload mass)/(mass carried aloft)	"intrinsic efficiency"
m_g/m_t	(mass of buoyant gas)/(mass of gas transport system)	"gas transport efficiency"
V_p/V_T	(payload volume)/(volume total balloon system)	"total volumetric efficiency"

Since the total balloon system comprises many items that are not quantitatively treated in this report (e.g., the launching subsystem) it will not be completely possible to evaluate m_T and V_T quantitatively. This deficiency should not prevent ranking alternative systems according to their calculated efficiencies, but it obviously influences the final conclusions (Chapter VIII), which purport to estimate how much mass and volume must be committed aboard the spacecraft in order to put a given payload aloft in the Mars atmosphere. Therefore, for numerical computations, m_T and V_T will first be computed as the sums of mass and volume for payload, balloon, and gas-transport subsystems, then both totals will be multiplied by a factor F to allow for "extras." (We adopt the conventional value F = 2.0 for numerical examples.)

In summary then, in this section we have attempted to provide an introduction to the theory of balloons—why they rise and float in an atmosphere and what forces affect them. Details of thermal effects and the dynamics of a rising balloon are treated in Appendixes A and C. In addition, we have derived a set of equations that express the general capabilities for performance of any balloon, and introduced the concept of total balloon system efficiency. In a later chapter, we shall examine the various types of balloons in detail with respect to their specific functions in performing several kinds of missions in the Martian atmosphere.

REFERENCES FOR CHAPTER II

2.1 Sinton, W. M., "Further Evidence of Vegetation on Mars," Science, Vol. 130, 1959, pp. 1234-1237.

2.2 Archimedes, εἰδική πληροφορία (215 B. C.).

2.3 Lamb, Sir Horace, Hydrodynamics, Dover Publications, New York, 1945.

III. MARS' ATMOSPHERE

Before considering balloon systems it is important to discuss the medium in which they will operate — in the present application, the atmosphere of Mars. Although very little is known directly, certain reasonable limits can be placed on its composition, and its variation of pressure, density, and temperature with altitude.* The purpose of the present report is to show the feasibility of balloon operations on the planet, not to design an actual balloon system. Therefore, although the present uncertainties about Mars' atmosphere are annoying, we can still present results in a parameterized way to permit a specific design when better information becomes available. We can also demonstrate feasibility by indicating how the extreme limits, as presently set, would affect balloon operation.

Since it is unlikely that a balloon system will be sent on the first capsule to enter the Martian atmosphere, we may hope that reasonably accurate information about the atmosphere will be available to the balloon designer before he has completed his final plans. It would be possible to design the system to have a reasonable probability of working even with the present uncertainties, but only at a considerable sacrifice in efficiency.

COMPOSITION

The only gas that has been definitely detected in Mars' atmosphere is CO_2. According to Grandjean and Goody's interpretation of Kuiper's 1952 results, the concentration of CO_2 is between 1 and 7 per cent by volume.[(3.3)] There is probably radiogenic argon; although there is no

*Authoritative reviews of current knowledge of the Mars atmosphere are given in Refs. 3.1 and 3.2.

direct evidence, most of the atmosphere is believed to be nitrogen.[3.4] On this assumption we will adopt 29 as the mean molecular weight of Mars' atmospheric gases.*

It is known that oxygen is no more than a minor constituent of Mars' atmosphere. The photodissociation of carbon dioxide, followed by the recombination of monatomic oxygen undoubtedly creates a trace of O_2, some of which may, in turn, be converted into ozone. Consequently, although neither gas has been detected on Mars, we assume a trace of oxygen, and we discuss the injurious effects of ozone in the chapter on balloon fabrics (Chapter VI).

Mars' atmosphere is also deficient in water vapor. Recent determinations by Dollfus[3.6] and Spinrad, et al.,[3.7] differ by a factor of more than 20, but even taking Dollfus' value, 200 microns depth of precipitable water vapor above the ground, Mars' atmosphere is exceedingly dry by terrestrial standards. We will assume that the atmosphere essentially lacks water vapor for the purposes of the present report.

TEMPERATURE

The mean equatorial ground temperature on Mars is about 230°K, although the diurnal temperature change may well be about 100°C.[3.8] The minimum ground temperature at night may be as low as 200°K, while the maximum during the day in the equatorial regions is about 300°K. The atmosphere near the ground will undergo somewhat smaller variations of diurnal temperature; at an unknown altitude (probably not over several kilometers above the ground) the atmosphere will remain at approximately the same temperature day and night.[3.9] Above this altitude its temperature decreases to the tropopause, which may be at a low altitude on

---

*A very recent interpretation of near infrared CO_2 high-dispersion absorption spectra by Kaplan[3.5] suggests that the Mars atmosphere may be much thinner than previously thought and may consist primarily of CO_2 and A. If this is the case, the mean molecular weight would be about 42.

Mars (several kilometers above the surface). Above the tropopause there may or may not be a well defined "mesosphere," as on Earth.[(3.10)] Since there is no direct information on the temperature distribution in the Martian atmosphere, calculations must rely (a) on analogy with the earth's atmosphere, (b) on setting "reasonable limits," or (c) on detailed calculations based on theoretical study of the radiative, convective, and conductive transport of heat vertically.

Conclusions drawn by analogy with Earth's atmosphere may well be misleading. Mesospheric heating on Earth arises from the absorption of solar radiation by ozone. Although there may be a trace of ozone in the Martian atmosphere, there is considerable disagreement about how it is distributed vertically.[(3.10)] Moreover, in the lower atmosphere, radiative heat transfer occurs in the infrared absorption bands of CO_2, which is present in much larger quantities on Mars than in Earth's atmosphere; whereas water vapor, by far the most important absorber of IR in the earth's atmosphere, is so deficient on Mars that it is ineffective. Thus, the value of an analogy between the temperature structures of Mars' and Earth's atmospheres seems dubious at the present time.

An entirely feasible approach, however, is to set limits with a reasonable hope that atmospheric parameters will fall between them, as Schilling did.[(3.9)] In the present report, we have assumed a 200—250°K temperature for the atmosphere near the surface; the atmosphere where "high-altitude" balloons would operate was assumed to be at 180°K.

DENSITY

We have chosen the values 1×10^{-5} gm/cm^3 for "high-altitude" balloon flights, 5×10^{-5} gm/cm^3 for "middle-altitude," and 8×10^{-5} gm/cm^3 for "low-altitude" balloon flights in this report. The question is: To what altitudes do these densities correspond on Mars? According to Schilling's Model II estimates, the "high-altitude" value is between 29 and 57 km, the "middle-altitude" value between 7 and 25 km, and the "low-altitude" value 15 km or less. Once the temperature distribution has been assumed along with density or pressure at the surface, calculation of the variation of density with altitude is a straightforward integration. In the lower atmosphere, the pressure uncertainty is more important, while in the upper atmosphere it is dominated by the temperature uncertainty.

RADIATION ENVIRONMENT

The solar constant outside Mars' atmosphere varies between about 0.7 and 1.1 cal cm^{-2} min^{-1} during the Martian year. The high haze layers in Mars' atmosphere will diminish this value somewhat.[3.11] We will use as the value at the surface 0.6—0.8 cal cm^{-2} min^{-1} (0.01—0.013 cal cm^{-2} sec^{-1}) for convenience.

The radiation environment of a floating balloon is changed markedly if a cloud passes overhead, if dust is raised on the surface under it, or if the atmosphere in which it is floating fills with dust. The radiative temperature of a dust cloud is appreciably lower than the surface,[3.12] an important consideration since dust storms are frequent on Mars. Since the balloon's temperature depends to some extent on the far-infrared radiation it receives from the ground, such a dust storm would act to lower the balloon temperature by reducing the ground radiation it received. If the air around the balloon were to become filled with dust, much of the sunlight would be cut off as well. High-altitude white clouds (usually assumed to be water clouds[3.4]) are rare occurrences.

Since the possible shielding effects of high haze and the quantity of oxygen and ozone are unknown, the flux of UV reaching Mars' surface is unknown, and may be considerable. A discussion of the consequences of intense UV in the lower atmosphere of Mars is, therefore, included in Chapter VI.

WINDS AND TOPOGRAPHY

Observations of cloud movements have given some information about wind conditions on Mars. Large-scale motions of dust clouds of 50 to 90 km/hr have been reported. A typical nonstorm wind velocity is believed to be 10 km/hr.[3.4] Theoretical calculations lead Mintz to speculate that in the summer hemisphere the general circulation may be in a stable regime, whereas during winter the circulation may break up into waves that would lead to storm systems.

By analogy with a high arid plateau on Earth, Schilling points out that there may be strong local winds at sunset and sunrise. On a small scale, analogy with desert regions on Earth suggests that small-scale gusts and "dust devils" may be common.

In considering launching methods we have given some note to the problem presented by winds — both steady winds and gusts.

Observation indicates that by Earth standards Mars is relatively flat. De Vaucouleurs states that there are probably no high mountains on the planet. Nothing is known of the small-scale topography, but considering the smoothing action of the frequent dust storms, it is probable that the surface is primarily gently rolling terrain. However, in order to allow for the possibility of rough topography, the problem of getting off the ground rapidly enough to be reasonably sure of avoiding obstacles is discussed in Appendix C.

ASSUMED MARTIAN ATMOSPHERIC CHARACTERISTICS: SUMMARY

1. Composition (mean molecular weight: 29)
   - 1—7 per cent CO_2, 1—6 per cent A, remainder N_2
   - trace amounts of O_2 and H_2O
   - possibility of a trace of O_3
2. Temperature, atmosphere and ground
   - ground: $230^{\circ}K$ mean
   - atmosphere near the ground: $200—250^{\circ}K$ (equatorial and mid-latitudes)
   - "high altitudes": $180^{\circ}K$ (inversions may occur)
3. Density of atmosphere
   - "low" atmosphere 8×10^{-5} gm/cm^3 (0 km—15 km)
   - "middle" atmosphere 5×10^{-5} gm/cm^3 (7 km—25 km)
   - "high" atmosphere 1×10^{-5} gm/cm^3 (29 km—57 km)
4. Radiation environment
   - solar constant: 0.01—0.013 cal cm^{-2} sec^{-1} (at surface)
   - low dust clouds fairly common
   - possibility of intense ultraviolet radiation in lower atmosphere
5. Winds
   - nonstorm: 10 km/hr
   - storm: 50—90 km/hr
   - frequent occurrence of strong local turbulence
6. Topography
   - no high mountains
   - mostly gently rolling terrain

REFERENCES FOR CHAPTER III

3.1 Kellogg, W. W., and C. Sagan, The Atmospheres of Mars and Venus, National Academy of Sciences—National Research Council, Publication 944, Washington, D. C., 1961.

3.2 Kellogg, W. W., and C. Sagan, "The Terrestrial Planets," Annual Revs. Astron. and Astrophys., in press.

3.3 Davis, M. H., "Properties of the Martian Atmosphere," Chapter VI in Studies of the Physical Properties of the Moon and Planets, Quarterly Technical Progress Report (4), The RAND Corporation, RM-2817-JPL, June 30, 1961.

3.4 de Vaucouleurs, G., Physics of the Planet Mars, The Macmillan Company, New York, 1954.

3.5 Kaplan, L. D., private communication.

3.6 Dollfus, A., "Mesure de la Quantité de Vapeur d'Eau Contenue dans l'Atmosphère de la Planète Mars," Compt. Rend. Acad. Sci., Vol. 256, April 1, 1963, pp. 3009-3011.

3.7 Spinrad, H., G. Münch, and L. D. Kaplan, "The Detection of Water Vapor on Mars," Astrophys. J., Vol. 137, No. 4, 1963, pp. 1319-1921.

3.8 Mintz, Yale, "A Note on the Temperature of the Equatorial Troposphere of Mars," Chapter XIII in Studies of the Physical Properties of the Moon and Planets, Quarterly Technical Progress Report (3), The RAND Corporation, RM-2769-JPL, April 28, 1961.

3.9 Schilling, G. F., Limiting Model Atmospheres of Mars, The RAND Corporation, R-402-JPL, August 1962.

3.10 Chamberlain, J. W., "Upper Atmospheres of the Planets," Astrophys. J., Vol. 136, No. 2, 1962, pp. 582-593.

3.11 Öpik, E. J., "The Atmosphere and Haze of Mars," J. Geophys. Res., Vol. 65, No. 10, 1960, pp. 3057-3063.

3.12 Sinton, W. M., and J. Strong, "Radiometric Observations of Mars," Astrophys. J., Vol. 131, No. 2, 1960, pp. 459-469.

IV. THE CHOICE OF BUOYANT GAS

The probable characteristics of the gaseous medium that will surround and support a balloon sent to Mars were reviewed in the chapter preceding. Before we look at balloons themselves, it is important to examine the gases that can be used to buoy a balloon, since the performance of a buoyant-gas balloon is markedly affected by the choice of gas. Of the factors relevant to the choice of gas, we select those we have found to be significant for discussion in this chapter.

As is demonstrated in Chapter II, a balloon's lift is governed by the difference between the densities of the gas inside and the air outside; this density ratio depends primarily on the molecular weight of the gas. Table 2 characterizes a number of light gases. It gives their molecular weights; β_0, the density ratio of outside air to balloon gas for equal temperatures; and "lifting efficiency," m_L/m. Besides these quantities, we must consider the weight and volume penalties incurred in transporting each gas from Earth. Methods for transporting possible balloon gases are analyzed in Appendix B. In this chapter, various gases are discussed, and the qualitative results of the analysis of gas transport are given.

FOUR BUOYANT GASES

Hydrogen

Hydrogen is by far the gas most favorable for balloon performance. It could be transported to Mars as a gas under high pressure, as liquid in a cryogenic system, or bound in a chemical compound, which is decomposed when hydrogen is needed. Analysis of these three methods (Appendix B) shows that high-pressure gas transport is generally inferior in efficiency to the others although it is considerably

Table 2

CHARACTERISTICS OF BALLOON GASES

Gas	Formula	M_g	β_0 [a]	m_L/m [b]
hydrogen	H_2	2.0	14.5	0.92
helium	He	4.0	7.25	0.84
decomposed ammonia	$\frac{1}{4}(N_2+3H_2)$	8.5	3.41	0.66
methane	CH_4	16.0	1.81	0.36
ammonia	NH_3	17.0	1.71	0.32
hot air	-	29.0	1.0 [c]	<0.17

(a) $\beta_0 = M_a/M_g$, the density ratio of air to gas assuming equal temperature.

(b) $\frac{m_L}{m} = \frac{\beta_0^*-1}{\beta_0^*}$, where $\beta_0^* = \beta_0(\frac{1-\lambda/2}{1+\lambda}) = 0.86\beta_0$ for $\lambda = 0.1$.

(c) The density ratio for a hot-air balloon is $\frac{T'}{T}$; a reasonable range in T' gives a density ratio up to about 1.4.

simpler. For relatively small quantities of gas, chemical gasogenes appear most efficient and convenient. For larger quantities, in the kilogram range, cryogenic transport of liquid hydrogen becomes practical. All of these methods require developmental research, as is discussed in Appendix B.

Under the assumption that methods such as those just mentioned can be satisfactorily developed, hydrogen appears to be the best choice of gas for the Mars balloon. In certain systems for Mars exploration, liquid hydrogen may be transported to the planet for use as fuel. In such a system, hydrogen might be essentially "free" for balloon filling. It should be noted that the drawback to the use of hydrogen in balloons on Earth, its explosive reaction with atmospheric oxygen, is not an important consideration for Mars.

Helium

Helium can be transported to Mars practically only as a gas under high pressure. However, analysis indicates that a balloon system using helium transported in pressure tanks would be inferior in efficiency to the more favorable hydrogen systems discussed above.

Ammonia

Of all the gases considered, ammonia is the easiest to transport because it liquifies at room temperature under pressure. Transport of the gas is, therefore, very efficient. But, in our assumed Martian atmosphere, this advantage is outweighed by its very low efficiency in providing lift because of its relatively high molecular weight. Another serious drawback is that temperatures in Mars' atmosphere may be so low that the condensation point of ammonia is approached.

Decomposed ammonia. Ammonia can be decomposed into 3 parts hydrogen, 1 part nitrogen (by volume) by catalysis at high temperature. The resulting mixture has been successfully used as a balloon gas on Earth, and might find similar application on Mars. The advantage of ammonia's ease of transport is retained, while the resulting mixture of gases has half the mean molecular weight of ammonia and will not condense.

Taking into account the entire system, including a heat source for the catalyst, the resulting balloon system appears inferior to the hydrogen systems already described. However, the use of decomposed ammonia is undoubtedly worth investigating in more detail than is possible here. The mixture of gases is considerably less efficient than hydrogen as a balloon gas, but the relative ease of transport and simplicity of the whole system might combine to make it appear favorable upon further study.

Methane

Methane is also relatively easy to transport as a liquid, but it is considerably inferior in total efficiency to hydrogen as a balloon gas.

HOT AIR

The hot-air balloon requires special treatment and is discussed in some detail in Chapter V. Although air (that is to say, Martian air) is available on the planet in any desired quantity, the means to heat it may have to be carried from Earth. In place of a gas-transport system, we then have a heater, fuel, and oxidizer. One attractive possibility, the use of solar power to heat the air, also is discussed in Chapter V.

GENERAL REMARK

For the numerical examples in the remainder of the present report, we will assume that hydrogen is used; that it is transported to the planet as a chemical gasogene for small quantities, and as a liquid for larger amounts.

V. BALLOON TYPES

Balloons may be classed in four categories: extensible, superpressure equal-pressure, and hot-air balloons. Although the last three might logically be classed as nonextensible balloons, and the hot-air type as a special case of the equal-pressure nonextensible balloon, the limitations and advantages of the four types differ greatly enough to deserve special treatment.

As was pointed out in Chapter II, balloons have a variety of potential uses in Martian exploration; the different types do not, in general, compete; each is suited for a particular mission. The extensible balloon is used for vertical soundings; the superpressure balloon provides a floating platform for experiments that require a long duration aloft; the equal-pressure balloon transports heavy payloads; and the hot-air balloon might find a similar use, if certain technical problems can be solved.

The Extensible Balloon

One particular type of balloon is that formed from an extensible, or stretchable, material. Such a balloon is inflated with a given mass of gas, is sealed, and is allowed to rise, with its volume increasing continuously, until it bursts. The equations of motion of such a balloon in a still atmosphere are essentially those derived in Chapter II. In performance, the extensible balloon differs from the nonextensibles in having no altitude of buoyant equilibrium. In function, its major peculiarity is the inherent differential pressure produced by the tension of the stretched material -- normally from the time it begins to rise.

Considering the depth of Earth's atmosphere and the altitude to which extensible balloons rise before bursting, the pressure differential never becomes a significant fraction of the ambient pressure; so it may be neglected when computing volume changes. On Mars, however, this will no longer be true. The thinness of Mars' atmosphere dictates that, by the time the balloon has risen to an altitude where the atmospheric pressure is two orders of magnitude less than the surface pressure, the differential pressure across the balloon material is of the same order of magnitude as the ambient pressure. When this is so, any consideration of volume change -- and hence, bursting altitude -- must take this pressure differential into account. In this section, then, will be considered the case of an extensible balloon rising in a thin atmosphere, as well as the relationships among the mass of the payload, the bursting altitude, the radius of the completely uninflated balloon, and the radius of the balloon at the moment of leaving the ground.

The mass of the gas in a balloon at the instant before it bursts is given by

$$m_g = \rho_f' V_b \ , \tag{5.1}$$

where V_b is the final volume of the balloon, and the subscript f refers to the final value of the parameter at the instant the balloon bursts. The final pressure inside the balloon is

$$p_f' = p_f\left(1 + \frac{\Delta p_f}{p_f}\right), \tag{5.2}$$

where Δp is the pressure differential across the balloon material. Using the perfect gas law, the equation expressing the final density inside the balloon is

$$\rho_f' = \rho_f \frac{M_g T_f}{M_a T_f'} \left[1 + \frac{\Delta p_f}{p_f} \right] . \tag{5.3}$$

Now, substituting Eq. (5.3) into Eq. (5.1) and letting $T_f'/T_f = \Lambda$, and $M_a/M_g = \beta_0$, we find that Eq. (5.1) becomes

$$m_g = \frac{\rho_f}{\beta_0 \Lambda} \quad V_b\left[1 + \frac{\Delta p_f}{p_f} \right] . \tag{5.4}$$

The mass of the gas with which the balloon was originally inflated to produce a specific λ is given by Eq. (2.8) in Chapter II,* as

$$m_g = \frac{m_L}{\beta_0^* - 1} . \qquad (5.5)$$

In this case, we assume that at the ground $T' = T$, and hence $\beta = \beta_0$. Since the balloon is sealed at the ground, we may set the m_g from Eq. (5.4) equal to the m_g from Eq. (5.5) and solve for m_p, the mass of the payload. Using the relation $m_L = m_p + 4\pi r_f^2 t_f \rho_b$,

$$m_p = (4/3)\pi r_f^3 \rho_f \left[1 + \frac{\Delta p_f}{p_f}\right]\left[\frac{\beta_0^* - 1}{\beta_0 \qquad \Lambda}\right] - 4\pi r_f^2 t_f \rho_b \quad , \qquad (5.6)$$

where r_f is the final balloon radius, t_f is the thickness of the fabric at the time it bursts, and ρ_b is the density of the fabric.**

The differential pressure across the fabric has been studied by Väisälä,(5.1) who found it to be given by

$$\Delta p = \frac{2t_u}{r_u} P \quad , \qquad (5.7)$$

---

*To take into account the pressure differential at the launching level, the equation for the mass of the gas should actually be

$$m_g = \frac{m_L}{\dfrac{\beta_0^*}{1 + (\Delta p_0/p_0)} - 1} ;$$

however, at the surface, $\Delta p_0/p_0 \ll 1$; hence, we can assume that the mass of the gas for an extensible balloon is given by Eq. (2.8).

**In Eq. (5.6) note that $\dfrac{\beta_0^* - 1}{\beta_0} = 0.86\,(m_L/M)$ for $\lambda = 0.1$ (See Table 2).

where t_u is the unstretched thickness of the fabric, r_u is the radius of the unstretched (uninflated) balloon, and P, a characteristic of the fabric, is dependent on the ratio q of the radius of the stretched balloon (at a given altitude) to its unstretched radius. With P expressed in atmospheres, Δp is given in atmospheres. Although P varies as a function of the fabric, its value rises generally to a maximum of about 3 atm when the balloon first starts to stretch, and, depending on the fabric, drops to a minimum of about 1 atm when q is between 3 and 6.

Since the mass of the fabric, as well as its density, is constant as the balloon expands, it is possible to establish the identity,

$$r_u^2 t_u = r_f^2 t_f ,$$

or

$$t_u = (q_f)^2 t_f , \text{ for } q_f = \frac{r_f}{r_u} .$$

Equation (5.7) becomes, then,

$$\Delta p = \frac{2(q_f)^2 t_f P_f}{r_u} .$$

Substituting in Eq. (5.6), we have then, for m_p,

$$m_p = (4/3)\pi q_f^3 r_u^3 \rho_f \left[1 + \frac{2q_f^2 t_f P_f}{r_u p_f}\right] \frac{\beta_0^* - 1}{\Lambda\beta_0} - 4\pi q_f^2 r_u^2 t_f \rho_b , \qquad (5.8)$$

an expression in terms of the balloon's unstretched radius, the final thickness of the material, the characteristics of the fabric, the type of gas used, and the burst altitude. Equation (5.8) permits balloon design for a given payload, or vertical range, or both.

Equation (5.8) may be used to examine the ability of an extensible balloon to carry a specific payload to a specific altitude on Mars. To do so, however, it is necessary to make certain assumptions regarding the values of the other parameters in this equation.

It has been found empirically that the thickness of an extensible-balloon fabric at the instant of burst, t_f, is between 0.5×10^{-3} cm and 10^{-3} cm, depending on the fabric used (rubber or neoprene; see Chapter VI). We shall assume that t_f is 10^{-3} cm. Again, from Appendix C, we will adopt a value of λ on Mars equal to 0.1. In Chapter VI, it is shown that, for extensible fabrics that have been used in the past, considering their "elongation-to-break," it is theoretically possible to achieve a q_f of approximately 6. Although this is not a conservative choice, it will be assumed here that $q_f = 6$ <u>subject to the temperature limitations of the materials</u>. The density of the fabric (ρ_b) will be assumed to be equal to 1.0, a value between that of natural rubber and that of typical synthetic rubbers. Finally, on the basis of the previous discussion of P, we shall assume that it is at its minimum value of 1.0 when the balloon bursts.

With these assumptions and Eq. (5.8), curves can be drawn showing the relationships between the payload mass (m_p) and the burst altitude for given values of the radius of the unstretched balloon. Figures 2 and 3 present the conditions assuming the gases used are H_2 and decomposed ammonia, respectively. For convenience, each figure also presents an altitude scale based on Schilling's Model II mean atmosphere.[5.2]

The curves show that as long as the payload mass is small, the burst altitude is determined essentially by the unstretched radius of the balloon. For a large payload mass, however, the burst altitude becomes an inverse function of payload mass. Figures 2 and 3 illustrate that the simple, extensible balloon may be capable of lifting useful payloads to interesting altitudes in the Martian atmosphere.

The optimistic picture presented by these curves, however, must be tempered by two reservations: (1) The ultimate ceiling of extensible balloons will be the altitude at which they have stretched to a radius six times the unstretched radius only if this altitude

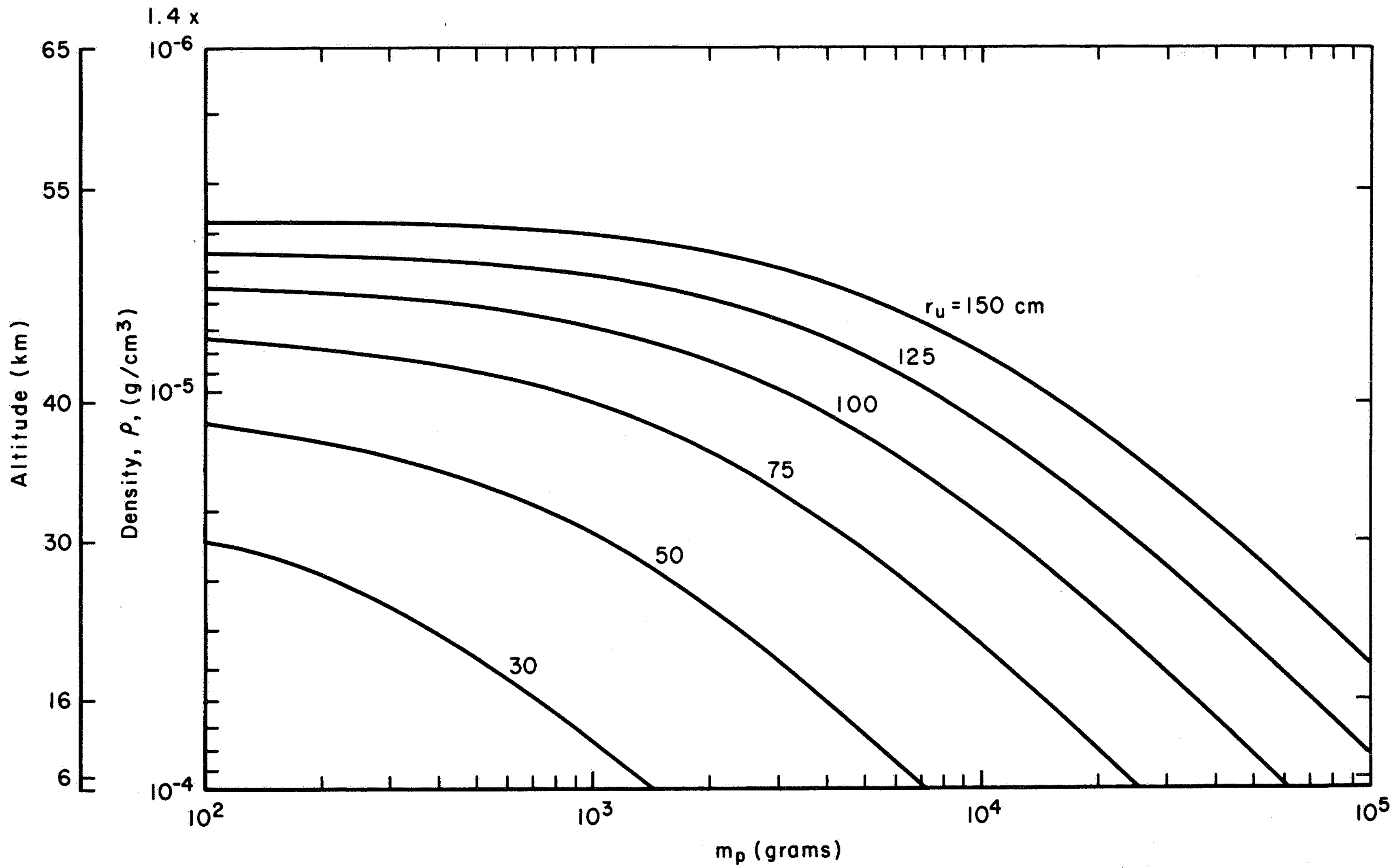

Fig. 2 — Relationship between payload mass and burst altitude of hydrogen-inflated extensible balloons. Curves represent balloons of six different unstretched radii

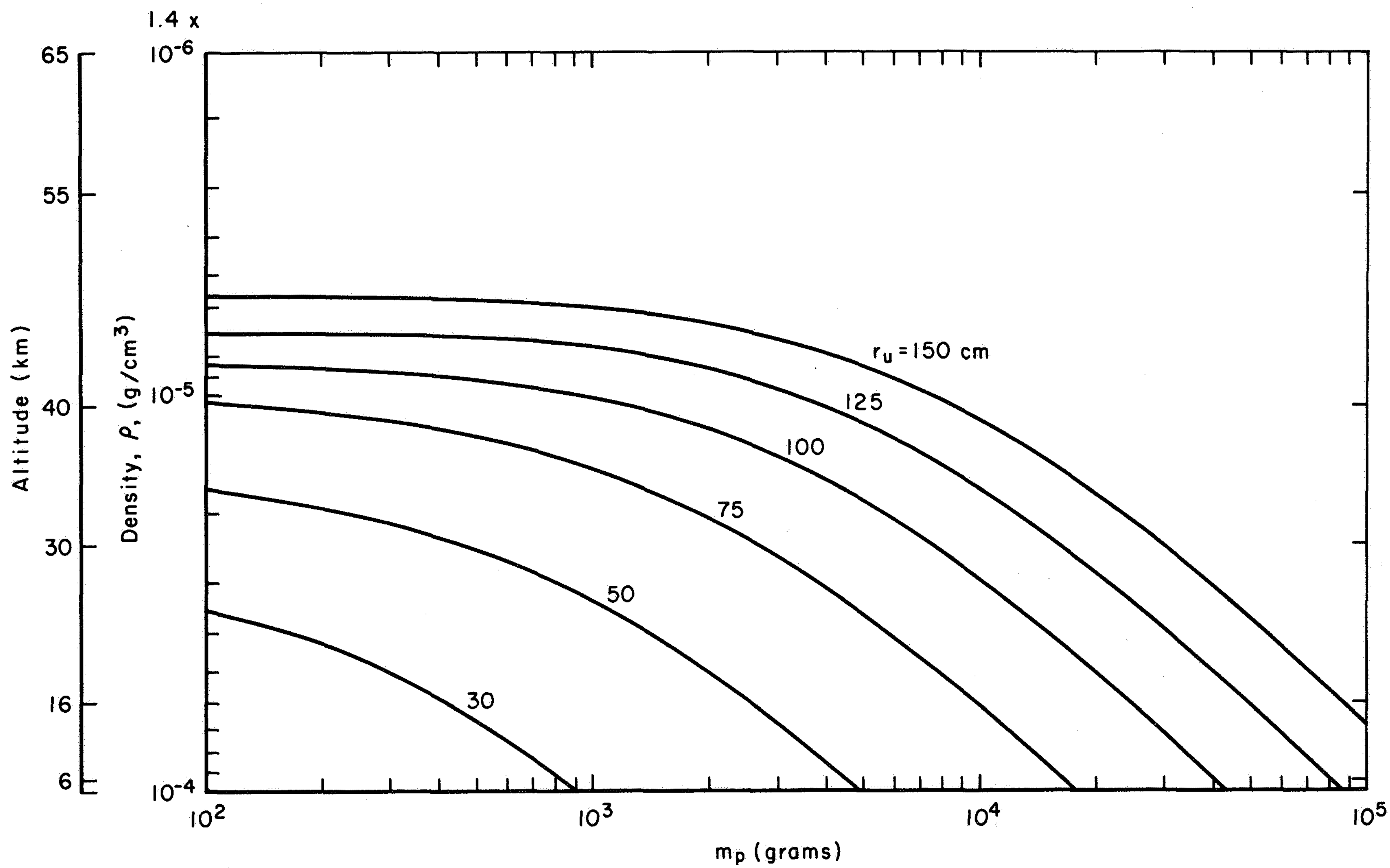

Fig. 3 — Relationship between payload mass and burst altitude of extensible balloons inflated with decomposed ammonia. Curves represent balloons of six different unstretched radii

is reached before the fabric reaches its imbrittlement temperature (approximately 230°K for familiar fabrics; see Chapter VI);* and (2) too great a concentration of ozone or too much ultraviolet radiation at balloon altitudes can damage the fabric, impair its elasticity, and thus necessarily reduce the burst altitude.

In considering the use of an extensible balloon on Mars, an additional constraint on a specific set of design parameters (other than desired payload and altitude) is that the balloon not reach a size before lift-off that will be unwieldy (see section on launching in Chapter VII). It is necessary, therefore, to examine the radius of the balloon newly inflated at ground level as a function of the achievable altitude and the unstretched radius. Remembering that the mass of gas remains constant in an extensible balloon, we may equate the mass of gas in the balloon on the surface and the mass of gas in the balloon at its final altitude [Eq. (5.1)] as

$$V_0 \rho_0' = V_f \frac{\rho_f}{\beta}\left(1 + \frac{\Delta p_f}{p_f}\right) .$$

Replacing ρ_0' by ρ_0/β (as before, it is assumed that $\Delta p_0 = 0$), we may immediately write an expression for r_0, the radius of the filled balloon on the surface, in terms of the final radius and the ratio of the density at the altitude to the surface air density:

$$r_0 = r_f \left[\frac{\rho_f}{\rho_0}\left(1 + \frac{\Delta p_f}{p_f}\right)\right]^{1/3} .$$

Utilizing the relationship between r_f and r_u (i.e., $r_f = q_f r_u$), and substituting the expression for Δp_f, we have, finally, an expression for the ratio of the inflated radius on the ground to the unstretched radius:

---

*If the balloon were at ambient temperature and the atmosphere were adiabatic, the material would become brittle at about 5 km (assuming a Martian surface temperature of 250°K). However, extensible materials used to date qualitatively appear to be quite black in the visible and infrared; so it appears certain that, by day, the material will be considerably warmer than the atmosphere. (See Figs. 9 and 10.)

$$\frac{r_0}{r_u} = q_f\left[\frac{\rho_f}{\rho_0}\left(1 + \frac{2q_f^2 t_f P_f}{r_u p_f}\right)\right]^{1/3} . \tag{5.9}$$

If we once again let $q_f = 6$, $p_f = 1$, and $t_f = 10^{-3}$, we may draw a set of curves as presented in Fig. 4, in which the ratio of r_0 to r_u is plotted as a function of the density at the burst altitude for given values of r_u. In this case, we have assumed that the surface density of the atmosphere on Mars is equal to 10^{-4} gm/cm^3. An examination of these curves, Figs. 2, 3, and 4, indicates that it may be feasible to design an extensible balloon system to lift payloads of a scientifically significant mass to useful altitudes on Mars, if the balloon is neither excessively large nor unwieldy.

Finally, by grouping together the terms in Eq. (5.8) that multiply r_u^3 and r_u^2, that equation takes on the form of Eq. (2.13), with

$$C_V = \frac{\rho_f q_f^3(\beta_0^* - 1)}{\Lambda\,\beta_0} \tag{5.10}$$

$$C_A = q_f^2 t_f \rho_b - \frac{2}{3}\,\frac{M_a q_f^5 P_f t_f(\beta_0^* - 1)}{\beta_0 T_f' R} \tag{5.11}$$

where R = the gas constant, 82.07 atm cm^3 deg^{-1} mole^{-1}. Therefore, from the product (μm_p), with $\mu = C_V^2/36\pi C_A^3$ [following Eq. (2.19)], reference to Fig. 1 gives the parameter ζ; whence r_u is readily computed following Eq. (2.17),

$$r_u = \frac{3C_V}{C_A(1 - \zeta)} .$$

The radius of the filled balloon on the surface, r_0, is found from Eq. (5.9). Here C_A contains a term that is not a part of the balloon load (the term that arises from the pressure differential

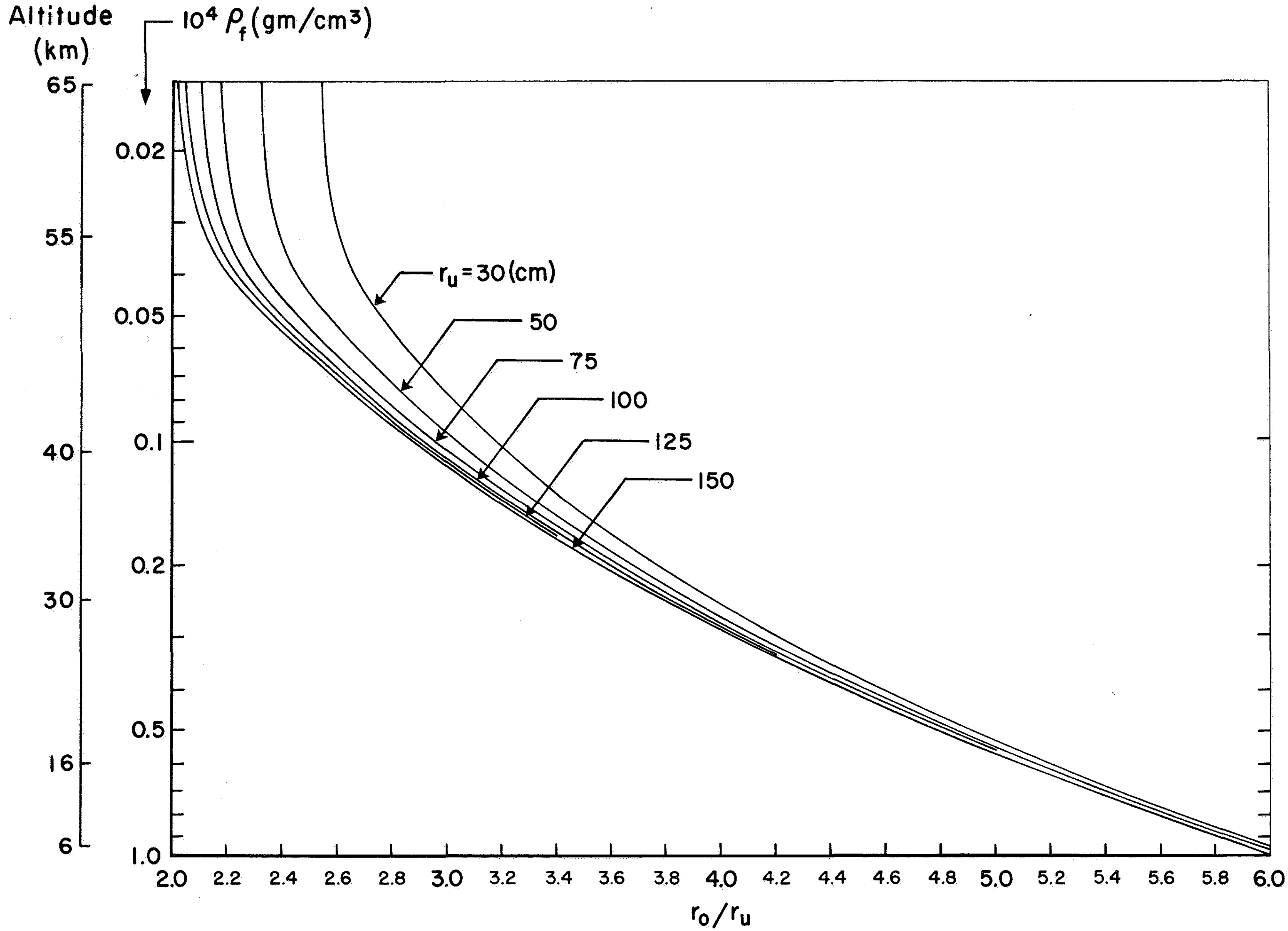

Fig. 4 — Ratio of initial balloon radius to unstretched radius plotted as a function of atmospheric density at burst altitude — shown for six values of unstretched balloon radii

across the fabric). Therefore, ζ is here not identical with the intrinsic efficiency m_p/m_L. This efficiency is, however, readily computed from the relation,

$$\frac{m_p}{m_L} = \zeta \left(\frac{m_p + 4\pi r_u^2 C_A}{m_p + 4\pi r_u^2 q_f^2 t_f \rho_b} \right) , \tag{5.12}$$

derived from Eq. (2.17).

The analysis just presented in terms of the "standard balloon equation", Eq. (2.13), greatly simplifies extensible balloon design since it gives the unstretched radius, r_u, and, through Eq. (5.12), the intrinsic efficiency, m_p/m_L, in terms of specified quantities; the environment at burst altitude, t_f, and other known quantities. Use of Fig. 1 eliminates the necessity of solving a cubic equation in r_u. The mass of gas used to fill the balloon is readily computed from the intrinsic efficiency, since

$$m_g = \frac{m_p}{(m_p/m_L)(\beta_0^* - 1)} , \tag{5.13}$$

an expression readily derived from Eq. (5.5).

The Nonextensible* Balloon

The behavior of a balloon made of material that resists stretching is quite different from that of the extensible balloon discussed in the previous section. The nonextensible balloon is inflated only partly before it leaves the ground. It rises until the gas inside expands to fill the balloon's fixed volume, and very soon afterward, reaches an equilibrium altitude.

Such balloons can be used for missions that include carrying both heavy payloads short distances and more moderate payloads for long periods. Two types of nonextensible balloons will be discussed in this section, the superpressure balloon, and the equal-pressure balloon. It will be noted that each has important application. For a sustained flight, or one where a consistent floating altitude is the first consideration, the superpressure balloon is better. However, for heavy loads, and for high reliability, where only relatively short flights are contemplated, the equal-pressure balloon might be chosen.

SUPERPRESSURE BALLOONS

General behavior. The superpressure balloon is a balloon of nonextensible fabric designed to float stably with an internal pressure always greater than that of the ambient atmosphere. How stability comes about is discussed later in this section.

As with other balloon types, the superpressure balloon's first

---

*The term "nonextensible" is, strictly speaking, a misnomer; the materials used for balloon fabric that resist extension typically exhibit a stress--strain relationship that is linear (Hooke's law) with increasing stress up to a "knee," beyond which the material undergoes plastic flow and quickly reaches the yield point. The knee occurs at a strain of 0.04 to 0.06 cm/cm and a stress of hundreds of atmospheres for both Mylar and polyethylene, representative balloon materials. There is, therefore, no significant error in calling a balloon made of this sort of material "nonextensible." (Extensible balloons, as discussed earlier, readily expand in radius up to 600 per cent.)

requirement is a quantity of gas sufficient to lift it rapidly (to avoid obstacles). This rate of rise in previous discussion has been related to λ, the ratio of the initial acceleration to local gravity. A value of λ equal to 0.1 is suggested in Appendix C; this value will be retained for the illustrative examples in this section.

At the launch the balloon is only partially filled. As it rises, the gas bubble inside expands, and eventually, the balloon rises to the altitude where the gas bubble completely fills the balloon. This altitude is called "the altitude of first full inflation." (It is here that the equal-pressure balloon begins to valve gas, thus maintaining pressure equality inside and out, as will be discussed later in this section.)

During the early part of the rise, the pressures are equal inside and outside of the nonextensible balloon, whether it is the equal-pressure or the superpressure type, although the gas temperature will generally not be the same as that of the atmosphere. From the altitude of first full inflation, the superpressure balloon continues to rise, but since it retains all of its gas, it begins to build an internal pressure that is progressively greater than that of the ambient atmosphere.

Stability when floating. The maximum differential pressure that a fabric can withstand depends on its tensile strength, so a preset valve, generally, is included in the design of a superpressure-balloon system, which prevents the internal pressure from exceeding a predetermined value. But the balloon rises even after gas is released, continuing to the altitude where the buoyant force becomes zero. By Eq. (2.1) the buoyant force is

$$F_B = (\rho V - m_g - m_L)g \ . \tag{5.14}$$

After the point of first full inflation is reached, V becomes approximately constant, V_b, and the balloon continues to rise (assuming no gas is valved, so m_g also remains unchanged) until

$$F_B = (\rho_m V_b - m_g - m_L)g = 0 \quad , \tag{5.15}$$

at the floating altitude (denoted here by the subscript m). The atmospheric density is expressible locally as an exponential function of altitude, z,

$$\rho = \rho_0 e^{-z/H_a} , \tag{5.16}$$

where ρ_0 is the density at some reference altitude, and H_a is the local atmospheric scale height. For small displacements from floating altitude, z_m,

$$F_B = - \frac{V_b \rho_m g}{H_a} (z - z_m) ; \tag{5.17}$$

so the balloon is subjected to a restoring force. Oscillations are damped by aerodynamic drag [not included in Eq. (5.17); see Eq. (2.11)].

Description of balloon flight. During the ascent of the balloon, the gas inside expands and the balloon temperature* can drop so low that buoyancy is lost. This problem was mentioned in Chapter II and is discussed in Appendix A. Such a loss of buoyancy will be a temporary state of affairs; the balloon will resume its rise when thermal equilibrium has been reestablished with the surrounding atmosphere. After the superpressure balloon reaches its floating altitude, its temperature, more than any other factor, governs its behavior. If the balloon is launched at night, it may reach its equilibrium altitude without valving gas. However, at sunrise, the balloon temperature will increase as solar energy is absorbed by the fabric. Then, the internal pressure increases proportionately, and if the pressure reaches the pre-set limit, gas is valved. Valving continues until the temperature reaches its maximum. Thereafter, if the balloon temperature never exceeds this value, no more gas will be valved.

---

*The expression "balloon temperature" is a short way of referring to the effective temperature of the gas inside the balloon. It is defined more precisely in Appendix A.

At sundown the balloon temperature drops rapidly, eventually reaching a minimum. The interior pressure varies directly with the temperature, provided the amount of gas is constant. If the balloon is to stay aloft, it must be so designed that with the amount of gas that remains after the daytime maximum, the internal pressure corresponding to minimum temperature is not less than the local atmospheric pressure. Otherwise, inasmuch as a balloon cannot sustain compression, it would become limp and lose buoyancy.

The balloon temperature varies through some range between the limits $(T')_{min}$ and $(T')_{max}$ during a one-day period;* the actual sequence of events during the first day will depend upon the time of launch. If the balloon were launched at night, the gas-valving operation would not be complete until temperature maximum the following day. Since the volume of the balloon remains approximately constant so long as it is taut, Eq. (5.15) shows that internal pressure changes do not bring about changes in floating altitude. A decrease in m_g means that neutral buoyancy occurs at an altitude where ρ_m is lower. So as the balloon valves gas, it rises; after the temperature maximum it floats at its ultimate altitude.

If instead the balloon were launched at noon, it could reach its ultimate altitude, completing the valving operation during its initial rise. If the first day's temperature maximum were exceeded on the second or subsequent day because of local meteorological conditions, gas would be valved again. But for long-duration design, we must try to estimate the maximum temperature that the balloon will ever reach during daytime, together with the minimum nighttime temperature, and design accordingly.

For flight duration of one full day or longer, encountering both high and low temperatures, the optimum superpressure balloon would

---

*$(T')_{min}$ and $(T')_{max}$ are here assumed to be the minimum and maximum temperatures that the balloon <u>ever</u> reaches -- they may not be reached in any <u>particular</u> day.

contain at floating altitude only as much gas as was required to maintain a positive pressure differential at the lowest balloon nighttime temperatures; and for lightness, its fabric would have a thickness no greater than required to withstand the maximum pressure when the balloon temperature was at its maximum.

<u>Superpressure balloon design fundamentals.</u> In the following paragraphs will be developed an approximate theory of superpressure balloon design.

For purposes of analysis, we can imagine that the launch occurs at any chosen time during a one-day period. The previous discussion shows that, although the detailed history of the flight depends upon the local time of the launch, the ultimate behavior (assuming a flight longer than 1 day) is independent of the launching time. For convenience, we will assume in the analysis to follow that the balloon is launched at night and that when it reaches its altitude of first full inflation, its temperature is at the minimum value.

The gas charge of buoyant gas introduced into the balloon at the time of launching is given by the expression

$$m_g = \frac{m_L}{\beta_0^* - 1} \quad , \tag{5.18}$$

where we have assumed that $T' = T$ at the ground.

The balloon is first <u>fully</u> inflated at an altitude where the atmospheric density, ρ_i, the amount of lifting gas, m_g, and the balloon volume, V_b, are related by the equation

$$m_g = \frac{\rho_i}{\beta_0} V_b \left(\frac{T_i}{T_i'}\right) \quad . \tag{5.19}$$

The last factor is the ratio of the ambient temperature to the mean equilibrium temperature of the confined gas. The subscript i refers to conditions at the altitude of the first full inflation. [By our assumptions, $T_i' = (T')_{min.}$]

Define

$$\chi = \frac{(T')_{min}}{T_i} , \qquad (5.20)$$

the ratio between the minimum balloon temperature and the ambient atmospheric temperature. In Appendix A, it is shown that a reasonable value for χ for Mylar is 0.85. From Eq. (5.19),

$$m_g = \frac{\rho_i V_B}{\beta_0 \chi} . \qquad (5.21)$$

By making use of Eq. (5.21), together with Eqs. (5.10), (5.18), (5.19), and (2.13), we can write

$$C_V = \frac{\rho_i(\beta_0^* - 1)}{\beta_0 \chi} , \; C_A = t_b \rho_b , \qquad (5.22)$$

where C_V, C_A are the coefficients introduced in Eq. (2.13). These coefficients enable us to analyze the balloon's performance by relating m_p to ζ as previously described.* And, as already discussed, they provide a ready access to other important quantities such as m_b,** and r, the balloon radius. Here, $\zeta = m_p/m_L$, the intrinsic balloon efficiency.

<u>Effects of finite material strength.</u> Now the limited strength of the fabric must be considered, as well as the requirements that the balloon neither burst at the maximum temperature and pressure nor become limp when low temperature reduces pressure to a minimum. The stress on the balloon fabric is related to the radius, thickness, and pressure differential by the expression

---

*For $\lambda = 0.1$, $\chi = 0.85$; $C_V \approx \rho_i \left(\frac{m_L}{m}\right)$.

**It should be noted that it is often found that the mass of the balloon fabric is an appreciable fraction of -- or may even exceed -- the payload mass.

$$\sigma = \frac{r(\Delta p)}{2t_b} . \tag{5.23}$$

It is necessary at all times that

$$\sigma \leq \sigma_{max} , \tag{5.24}$$

where σ_{max} is the maximum allowable stress in the fabric.* If the quantity of gas is constant (after a one-day cycle) the maximum pressure differential $(\Delta p)_{max}$ is related to $(\Delta T)_{max}$, $[(T')_{max} - (T')_{min}]$, by the expression

$$\frac{(\Delta T)_{max}}{\chi T_i} = \frac{(\Delta p)_{max}}{p_i} , \tag{5.25}$$

in terms of the pressure and the temperature of the atmosphere at the altitude of first full inflation. This equation can be written

$$(\Delta p)_{max} = \frac{\rho_i R}{\chi M_a} (\Delta T)_{max} . \tag{5.26}$$

Combining this expression with Eq. (5.23), we find that the requirement that the stress in the fabric be less than σ_{max} sets a limit on the balloon radius,

$$r \leq \frac{2t_b \chi M_a \sigma_{max}}{\rho_i R(\Delta T)_{max}} . \tag{5.27}$$

This limit on the permissible balloon size sets a corresponding limit on the maximum payload. Using Eqs. (2.17) and (5.22), we have

$$\frac{m_p}{m_L} \leq 1 - \frac{3\Delta T_{max}\beta_0\rho_b R}{2M_a(\beta_0^* - 1)\sigma_{max}} . \tag{5.28}$$

*For Mylar, a typical plastic used for superpressure balloons, σ_m is several thousand atmospheres; see Chapter VI.

The quantity $(\Delta T)_{max}$, the maximum temperature range, is a function of the environment of the balloon in the planetary atmosphere (primarily the radiation environment) and the balloon fabric used; and unless the fabric is completely "black," it will depend also on the fabric's thickness, t_b. See Appendix A for a discussion. To permit estimation of $(\Delta T)_{max}$, the balloon's effective absorptivity of sunlight and its emissivity of far-infrared radiation should be determined in the laboratory.

The pressure-release valve is set in accordance with $(\Delta T)_{max}$, following Eq. (5.26). The value for $(\Delta p)_{max}$ computed from Eq. (5.26) assures that the balloon is at all times in the taut condition, and, if the design is such that the inequality (5.28) is satisfied, the stress in the fabric never exceeds safe limits.

The ultimate equilibrium floating altitude, allowing for possible valving of gas, will be where the atmospheric density is given by

$$\rho_m = \frac{m_L}{V_B\left(1 - \frac{1}{\beta_0\chi}\right)} , \tag{5.29}$$

and it is readily shown that

$$\rho_i = \left(\frac{\beta_0\chi - 1}{\beta_0^* - 1}\right) \rho_m ; \tag{5.30}$$

so in the equations previously derived, e.g., Eq. (5.22), the density at the ultimate floating altitude, ρ_m, can be specified rather than ρ_i, the density at first altitude of full inflation.

Thickness of the balloon fabric. The design is most efficient when m_p/m_L equals the right side of expression (5.28). This value can be achieved for a given payload by choosing the thickness of fabric appropriate to that payload. That is, a certain thickness, t_b, can be found that maximizes the efficiency of carrying a given payload if the other parameters of the balloon system have been specified. At this point, it is necessary to introduce two more limits, the limits marking off the feasible range of thicknesses of balloon fabrics.

It is found (see Chapter VI) that every balloon material has a minimum usable thickness; thin material is excessively vulnerable to abrasion and other damage. Similarly, every material has a maximum thickness beyond which it cannot be successfully fabricated. These limits on thickness have important implications: for low values of the payload mass, the argument outlined above would lead to a choice of low values for t_b in order to maximize m_p/m_L; the minimum value that t_b can have, $(t_b)_{min}$, sets a limit on how far this process can go. On the other hand, the maximum value of t_b sets an ultimate maximum on the size of payload that the superpressure balloon can be designed to carry.

This limit on maximum payload is one disadvantage of the superpressure balloon. Another disadvantage arises from the somewhat inferior reliability of suitable fabrics. Polyethylene, which is a highly reliable plastic film, is unsuitable for the superpressure balloon because of its inferior strength. Mylar, on the other hand, although tremendously strong, is difficult to fabricate reliably partly because of a tendency for highly stressed points to occur on the seams. As a result, Mylar superpressure balloons do not at present have the reliability of polyethylene equal-pressure balloons. Reliability is so important in space experiments that research should be directed toward improved methods of fabricating stress-free balloons and developing plastic films that are both strong and reliable.

We conclude this section with a numerical example. Figure 5 shows a plot of m_p/m_L versus m_p for a balloon of Mylar, a representative superpressure balloon material, inflated with hydrogen. On the graph are two curves, one each for minimum and maximum thicknesses (conservatively set at 0.0015 cm and 0.004 cm). The density altitude of first full inflation was assumed to be 5×10^{-5} gm/cm^3, and χ was assumed to be 0.85; $\sigma_{max} = 1000$ atm, a conservative value, was adopted. The limiting size, fixed by the finite tensile strength of the material, is determined by the value of $(\Delta T)_{max}$ as shown in the inequality (5.28). This limit is indicated on Fig. 5 for two values of $(\Delta T)_{max}$, 22°C, as predicted by the approximate analysis of Appendix A, and double this value, 44°C. As has been mentioned, further

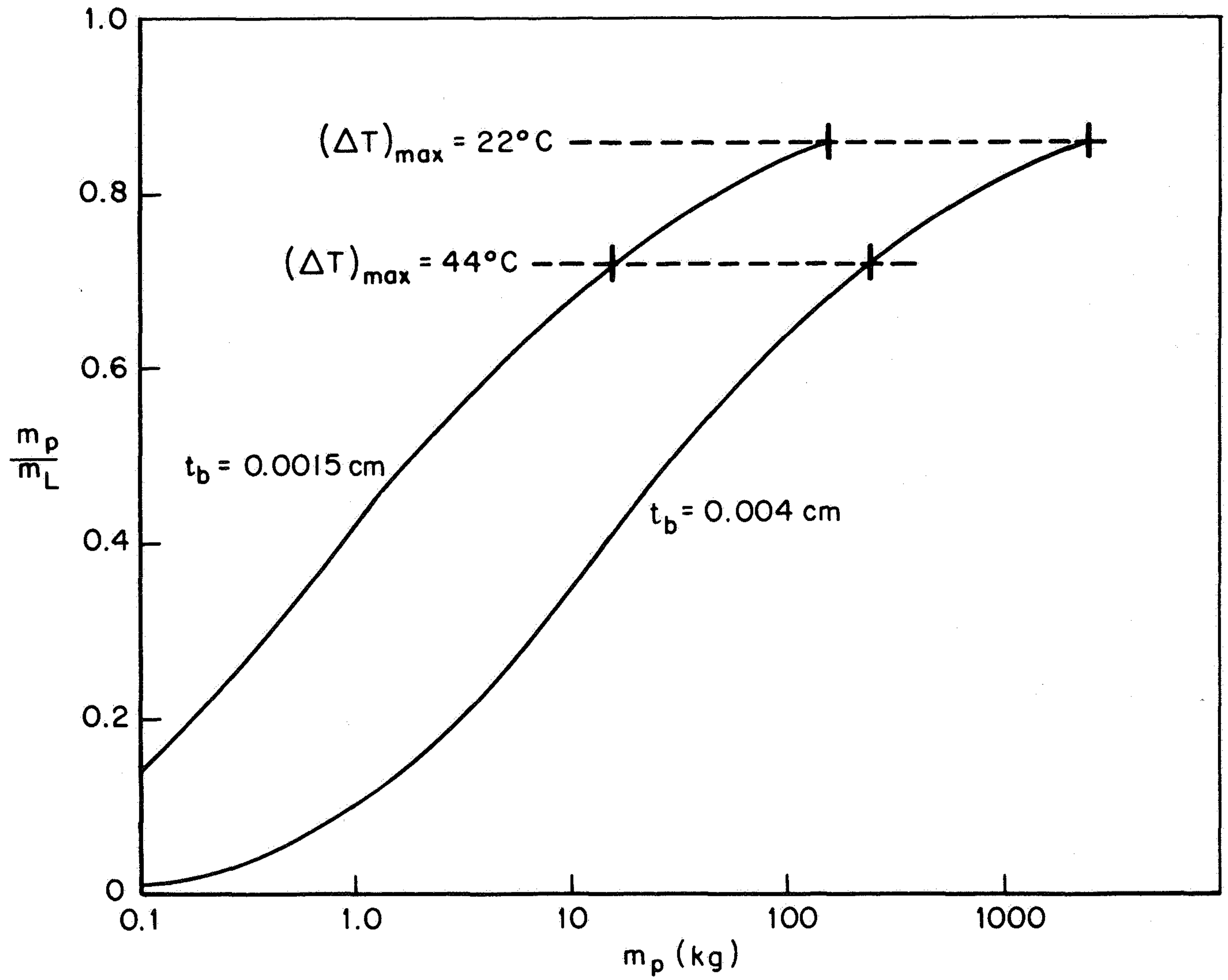

Fig. 5 — Intrinsic balloon efficiency as a function of payload for a hydrogen-filled superpressure Mylar balloon at a density altitude 5×10^{-5} gm/cm^3. Two fabric thicknesses are shown as well as the maximum efficiency payload limits set by two values of $(\Delta T)_{max}$

research into the radiative properties of balloon-fabric materials is required before $(\Delta T)_{max}$ can be estimated with confidence. The figure shows that for t = 0.0015 cm, if $(\Delta T)_{max} = 22°C$, the maximum payload is about 160 kg (if Eq. (5.27) is used, the limiting radius is about 8.0 meters).* On the other hand, if $(\Delta T)_{max}$ is 44°C, the maximum payload is diminished by a factor of 10 to 16 kg (r = 4m). This example illustrates the importance of knowing accurately the radiative properties of the balloon material and the radiative environment in which it will operate. It also emphasizes the necessity for conservative design to allow for greater than anticipated temperature fluctuations.

EQUAL-PRESSURE BALLOONS

General discussion. The equal-pressure balloon can be considered in some respects to be a special case of the superpressure balloon; it is the case where $(\Delta p)_{max} = 0$; that is, the internal pressure is not allowed to be greater than the pressure of the atmosphere. During ascent, the two types of balloon behave alike. Both rise to the altitude of first full inflation. At this point, the equal-pressure balloon must begin to valve gas; it continues rising to an equilibrium floating altitude, where the buoyant force becomes zero and pressure is equalized inside and out.

So long as the balloon temperature stays the same or increases with time, the equal-pressure balloon is stable. As its temperature increases, more gas is vented, of course, but the balloon remains fully inflated. However, should the temperature decrease, the gas within the balloon would contract, and the balloon would become limp and lose buoyancy. As the limp balloon falls, the work done by the atmosphere on the balloon gas in compressing it will raise its temperature; so if the atmospheric lapse rate is low or negative

---

*For this case $\mu = 2\ kg^{-1}$; reduced radius $[r(1 - \zeta)] = 1.1$ meters approximately; the quoted values for $(m_p)_{max}$ and the corresponding r are derived from these quantities using the limiting ζ.

the balloon may find another lower buoyant level. Where there is a temperature inversion, for example, the balloon could enter an atmospheric layer sufficiently cooler outside than inside to make it again buoyant. However, in general, for the balloon to stay aloft after a drop in temperature, it must drop ballast. The equal-pressure balloon cannot be used for long-duration missions without ballast; for shorter flights, however, it can be used (as on missions that can terminate at the first sunset).

The "slightly pressurized" balloon. Rather than continuing to concentrate on the case of the purely equal-pressure balloon, we will confine our attention to the case of the equal-pressure balloon in which the gas pressure is actually above -- but only slightly above -- the pressure of the ambient atmosphere. The eventual instability of the purely equal-pressure balloon brought about by its loss of gas during any small temperature increase could be partially alleviated by designing the balloon to operate in this way. The difference between this type of equal-pressure balloon and the superpressure type discussed in the previous section is this: the pressure-release valve and the thickness of fabric of the super-pressure balloon are so specified that the balloon will neither burst nor become limp. In the balloon type here under consideration, the thinnest fabric practical for manufacture would be chosen; then the valve would be set to protect the balloon from bursting. No provision would be made in the design to keep the balloon taut through its temperature cycles.

The advantages of the equal-pressure balloon (modified as suggested above) are that

(1) the balloon can be made of the thinnest material feasible.

(2) it can be made of a type of material that, because of low tensile strength, is unsuitable for the superpressure balloon (e.g., polyethylene).

(3) there is no payload maximum set by the maximum allowable thickness of the fabric.

The disadvantages are that (1) there is no inherent, long-term stability; if the balloon is to float past sunset, ballast must be dropped; and (2) the balloon does not float at a constant density altitude; its altitude varies widely when it descends at sunset and then rises after ballast is dropped.

Theory. The theory developed for the superpressure balloon can be readily carried over to the slightly pressurized case. The efficiency m_p/m_L for a given payload m_p is given as before, except that here

$$C_V = \frac{\rho_i(\beta_0^* - 1)}{\beta_0} . \qquad (5.31)$$

As before, $C_A = \rho_b t_b$. The chosen thickness, t_b, will now ordinarily be the characteristic minimum thickness for the fabric that has been selected. The curve in Fig. 5 corresponding to $t_b = 0.0015$ cm, without the maximum limit imposed as in the superpressure case, would apply approximately for Mylar used in the equal-pressure balloon. (The factor $\chi = 0.85$, used in the superpressure case, should be omitted for the equal-pressure case. The error incurred is, however, small, and the curve gives a good approximation of equal-pressure balloon performance.)

Since no provision is made to keep the balloon taut under all temperature conditions, the inequality (5.28) does not apply. The pressure-relief valve for the slightly pressurized balloon would be set on the basis of Eq. (5.23), rather than Eq. (5.25):

$$(\Delta p)_{max} = \frac{2t_b\sigma_{max}}{r} ,$$

where r is computed using C_V and C_A following Eq. (2.17).

FLIGHT DURATION

The mission of a nonextensible balloon may make it important for the balloon to remain aloft through several gas-temperature cycles (i.e., several sunrise--sunset cycles). It is necessary, therefore, to determine the penalty paid in decreased balloon performance to achieve a given duration.

<u>Flight duration for equal-pressure balloons.</u> As described previously, the flight duration for an equal-pressure balloon depends on the proper correction for the instability that occurs at each sunset. If we differentiate Eq. (2.5) with respect to temperature, we find that a change in temperature of the gas equal to ΔT produces a force imbalance in the floating-balloon system (at the first sunset encountered) equal to

$$\Delta F_B = \frac{gm_L\beta}{\beta - 1} \left(\frac{\Delta T}{T'}\right) , \tag{5.32}$$

requiring, for equilibrium to be restored, the removal of a mass* equal to

$$\Delta m_L = m_L\gamma , \tag{5.33}$$

where

$$\gamma = \frac{\beta}{\beta - 1} \left(\frac{\Delta T}{T'}\right) .$$

At the next sunrise the balloon, relieved of a mass Δm_L, and with the ΔT restored by means of absorption of solar radiation, will rise to a somewhat higher altitude than the previous day, valving some gas as it does so. On the day following the first sunset, the mass of gas contained in the balloon is equal to

$$\frac{m_L}{(\beta - 1)} (1 - \gamma) . \tag{5.34}$$

This process will be repeated at each sunset and sunrise, until on the day following the $D^{\underline{th}}$ sunset,

$$0 = (m_g)_D(\beta - 1) - m_L(1 - \gamma)^D . \tag{5.35}$$

*While it is true that the equilibrium can be restored by replacing the heat lost by the gas, it is demonstrated in the section on hot-air balloons that this is very costly in terms of committed mass. For this reason it was felt desirable to restrict this discussion of the duration of equal-pressure balloons to the case of equilibrium acquired through the use of expendable mass (ballast).

If the desired duration includes D sunsets, then the total mass remaining, $(m_L)_f$ [i.e., m_L minus an expendable mass $(m_e)_D$], after this period is given by

$$(m_L)_f = m_L(1 - \gamma)^D \ , \tag{5.36}$$

and the total expendable mass or ballast that must be carried is

$$(m_e)_D = (m_L)_f \left[(1 - \gamma)^{-D} - 1\right] \ . \tag{5.37}$$

Utilizing Eq. (5.36), it can easily be shown that the mass that must be dropped on the $n^{\underline{th}}$ night following the launching is given by

$$\frac{(m_L)_f}{(1 - \gamma)^{D-n+1}} \ . \tag{5.38}$$

The payload mass is defined as

$$m_p = (m_p)_D + (m_e)_D \ , \tag{5.39}$$

where $(m_p)_D$ is the nonexpendable payload mass available for a duration of D sunsets. We can express the ratio of the available payload to the total payload as

$$(m_p)_D/m_p = \left[(1 - \gamma)^D/\zeta\right] - (1/\zeta) - 1 \ , \tag{5.40}$$

where ζ is m_p/m_L. For $\gamma \ll 1$, the normal condition,

$$(m_p)_D/m_p = 1 - D\gamma/\zeta \ . \tag{5.41}$$

Under these conditions, the "intrinsic efficiency" for a given duration (here defined as the ratio of the mass of the useful payload to the total initial balloon load) is

$$\frac{(m_p)_D}{m_L} = \zeta - \left[1 - (1 - \gamma)^D\right] \approx \zeta - D\gamma \ . \tag{5.42}$$

It should be noted that $(m_p)_D$ goes to zero for $D = \zeta/\gamma$. Therefore durations, measured in sunsets, longer than the integer part of (ζ/γ) are impossible.

Flight-duration for superpressure balloons. A properly designed superpressure balloon, as described previously, should theoretically not destabilize at sunset. In principle, then, the involuntary termination of the flight of such a balloon should result only from the deterioration of the material or the loss of gas (hence of pressure) due to the fabric's permeability or to actual leaks.

The deterioration of the fabric because of exposure to ultraviolet radiation and ozone is discussed in Chapter VI. While such deterioration does occur, and in the long run may determine the ultimate limit of the balloon's flight, it is not possible with present knowledge to determine this maximum duration.

Recognizing the probable effect of fabric deterioration on a balloon's flight duration, but for the moment leaving that problem for future research, we can consider the limitations imposed on a superpressure balloon's flight by loss of gas. Experience shows there are two rather effective methods of eliminating balloon leaks. The first of these is to impose adequate quality controls in the manufacture of the plastic film and the fabrication of the balloon, combined with thorough inspection of the balloon throughout construction and packaging. The second method recognizes that small "pinholes" in the film, if they occur in manufacture, will be random, and can be virtually eliminated by the lamination of two thinner sheets of plastic. From this experience follows the assumption that, for this application, leaks may be minimized.

Using the value to be given in Chapter VI for the permeability of Mylar to hydrogen, the flight duration, if limited solely by diffusion of the gas through the film, can be shown to be several thousand years. It is evident, therefore, that the duration of flight of a superpressure balloon is completely determined by fabric deterioration or inadvertent leaks.

The Hot-Air* Balloon

The earliest balloon ascents, by the Montgolfier brothers in the 18th century, were in hot-air balloons. During the next two hundred years, many hot-air balloon ascents were made, but this type of balloon eventually was abandoned except at carnivals and fairs. Only during the past several years has interest revived, first for sport ballooning, and more recently for short-duration transport of heavy loads.[5.3] In contrast with the light-gas balloons, the hot-air balloon relies for lift entirely on the temperature differential between the atmospheric gases inside the balloon and the air outside. The air inside is heated, and thus is made less dense than the air at the same pressure outside -- this density difference provides lift in a manner entirely analogous to the lighter-than-air gas balloon. In operation, air is warmed and pumped into the balloon envelope -- then heat is continuously supplied to make up for convective and radiative losses. The balloon rises and floats at the altitude where it is neutrally buoyant. If heat is supplied by a fuel burner, when the fuel has been exhausted the balloon will lose buoyancy and descend to the ground.

In the following paragraphs we will discuss the basic equations governing the behavior of the hot-air balloon once it has reached its floating altitude, and derive equations relating the size of the balloon, the duration of the flight, the payload, and the optimum operating temperature. The possibility of using a sun-heated balloon is discussed briefly.

---

*In the interest of simple terminology we here extend the meaning of "air" to include the atmospheric gases of Mars.

BASIC THEORY

The basic requirement for hot-air balloon operation is the replacement of heat losses. Heat is lost in several ways: (1) cooling by radiation, (2) heat loss from the fabric to the surrounding atmosphere by free convection, or (3) mixing of cool outside air with the air inside the balloon if it is open at the bottom. To balance these losses, heat can be supplied by (1) fuel combustion, (2) absorption of solar radiation by day, (3) absorption of infrared radiation from the ground.

The balloon buoyancy equation may be written:

$$\rho V_b \frac{\theta}{T + \theta} - m_B - m_f - m_{tp} - m_b - m_p = 0$$

where

m_B = burner mass,

m_f = mass of fuel plus oxidizer,

m_{tp} = mass of tankage and plumbing,

θ = balloon superheat (difference between mean temperature of air inside the balloon and air outside).

The other symbols have their usual meanings.

We will treat the hot-air balloon problem very simply, ignoring the many complications involved in the air circulation within the balloon, the heat-transfer details, etc. Nevertheless, the simplified theory presented should permit estimation of such parameters as balloon size and fuel requirements.

The following are expressions for the various terms that together determine the balloon's mean temperature (see Appendix A for further discussion).

Terms giving the rate of heat loss

radiative-heat loss:	$\sigma_B \epsilon_b A_b T_r^4 = \sigma_B \epsilon_b A_b \eta_r (T+\theta)^4$
convective-heat loss:	$K_c A_b \eta_c \theta$
cool-air mixing:	(probably of the same form as the convective-loss term)

where η_c is a factor to allow for a difference between the mean temperature of the air within the balloon ($T' = T + \theta$), and the mean fabric temperature T_b. Such a difference might be significant if heat were supplied by a high-temperature heating element within the balloon. (η_r fills a similar function for radiative losses.) The other symbols are defined and discussed in Appendix A.

Terms giving the rate of heat gain

by fuel combustion:	$\dot{m}_f/K_Q$
by absorption of solar radiation:	$1/4\ \alpha_b S A_b$
by absorption of IR from the ground:	$1/2\ \epsilon_b \sigma_B A_b T_G^4 = 1/2\ A_b S_G \epsilon_b$

where $\dot{m}_f$ = mass rate of consumption of fuel and oxidizer, K_Q = reciprocal heat of combustion (in grams/calorie), and S_G = ground integrated radiation. The other symbols are discussed in Appendix A.

Assuming a constant combustion rate and a duration of τ seconds,

$$m_f = A_b K_Q [\sigma_B \epsilon_b \eta_r (T + \theta)^4 + K_c^* \theta - \frac{\alpha_b}{4} S - \frac{\epsilon_b}{2} S_G] \tau \quad ,$$

where K_c^* is K_c modified by including cool air mixing and η_c.

The tankage mass, m_{tp}, will be included by multiplying m_f by a suitable factor; for convenience this factor will be absorbed into K_Q, which we then write K_Q^*. The burner mass, m_B, is approximately proportional to the rate of heat generation, which, in turn, is equal to the net rate of heat loss; the factor of proportionality will be symbolized K_B. Assuming spherical symmetry, as usual, the buoyancy equation assumes the form

$$\frac{4}{3} \pi r^3 C_V - 4\pi r^2 C_A - m_p = 0 \quad , \tag{5.43}$$

with

$$C_V = \frac{\theta\rho}{T + \theta} ,$$

$$C_A = (\sigma_B \epsilon_b \eta_r (T + \theta)^4 + K_c^* \theta - \frac{1}{4}\alpha_b S - \frac{1}{2}\epsilon_b S_G)(K_Q^* \tau + K_B) + t_b \rho_b \quad .$$

OPTIMUM SUPERHEAT

The balloon's size is dependent on a number of parameters, but for a given fabric, altitude, payload, fuel and fuel system, solar constant, ground emission, and ambient air temperature, the only parameter left unspecified is the superheat, θ. A high θ implies greater buoyancy than a low θ, so a higher superheat might be expected to permit a smaller balloon radius and, hence, a more efficient system. However, a high balloon superheat also means a high rate of heat loss per unit area, and, hence, a proportionately large fuel requirement for a given duration. There is an optimum choice of balloon superheat for which the total system will have the smallest total mass for a given payload and flight duration.

During the day, even if no heat is added by burning fuel, the balloon will frequently achieve a higher temperature than the surrounding air if it absorbs radiation readily in the visible part of the spectrum but absorbs and emits poorly in the far infrared. Although apparently never exploited on the earth, a sun-powered hot-air balloon appears possible. Such a balloon would be designed so that heat losses are replaced by absorption of sunlight; its possible performance is discussed later in this chapter. Figure 6 shows how the superheat, θ_s, in equilibrium with sunlight and infrared radiation from the ground, depends on ϵ_b, α_b of the fabric.* Such temperature calculations are tentative only, since the treatment is oversimplified and many uncertainties remain. However, they serve

---

*The surrounding air was assumed to be at 250°K, the radiative ground temperature was 220°K. The value K_c was assumed to be 1.5×10^{-5} cal cm^{-2}sec^{-1}deg^{-1}. These are all "pessimistic" values. The solar constant was assumed to be 0.01 cal cm^{-2} sec^{-1}.

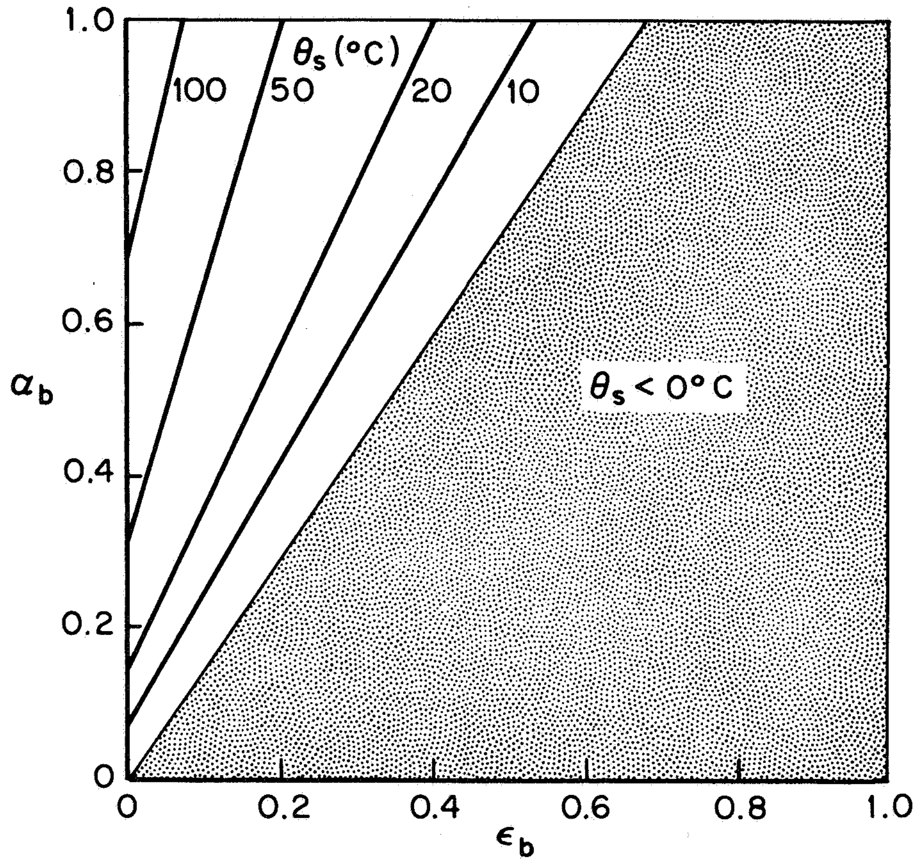

Fig. 6 — Superheat of a hot-air balloon, θ_s, for various absorptive and emissive powers under the specified set of assumptions

to illustrate the possibility of achieving high superheats during the day without fuel consumption. If θ_s is positive, the optimum balloon superheat for daytime operation is clearly not less than θ_s. Besides the load aloft, we should include in the total mass of the balloon system the mass of a special blower and burner, and a charge of fuel and oxidizer to fill the balloon with hot air initially. (If the balloon is filled by "ramming in air" during the initial descent through the atmosphere, the blower would be superfluous, but the heater and fuel would still be required.) The equipment for initial heating and inflation can be jettisoned and so is not included in the load aloft; we symbolize its mass by m_{ad}.

The volume of the inflated balloon can be expressed [see Eq. (2.20)]

$$V_b = \frac{m_p}{\zeta\, C_V} .$$

The quantity of heat required to raise the air in the balloon θ degrees above the ambient temperature is

$$V_b \left[\frac{\rho\, T}{T + \theta}\right] C_p \theta .$$

Therefore,

$$m_{ad} = f_{BB}\, \rho \left(\frac{T\theta}{T + \theta}\right) C_p \frac{K_Q m_p}{\zeta\, C_V} ,$$

where f_{BB} allows for the mass of the blower, extra burner, and tankage. We can rewrite this equation, substituting C_V from Eq. (5.43),

$$m_{ad} = f_{BB} T C_p K_Q \frac{m_p}{\zeta} .$$

Since the total system mass, m_T, is equal to $m_L + m_{ad}$,

$$m_T = \frac{m_p}{\zeta} \left[1 + f_{BB} T C_p K_Q\right] . \tag{5.44}$$

Therefore, to minimize the total mass m_T for a given m_p, we must maximize ζ. And, since the relationship between μm_p and ζ is monotonic and increasing, the same thing is accomplished for a given payload by maximizing μ.

To solve the optimization problem analytically, we can approximate the quartic term by a linear expression over a limited range in θ:

$$\sigma_B \eta_r (T + \theta)^4 \approx J_0 + J_1 \theta . \tag{5.45}$$

As before,

$$C_V = \frac{\rho \theta}{T + \theta} .$$

Now write

$$C_A = K_0 + K_1 \theta ,$$

where

$$\begin{aligned} K_0 &= \left(\epsilon_b J_0 - \frac{1}{4} \alpha_b S - \frac{1}{2} \epsilon_b S_G \right) \left(K_Q^* T + K_B \right) + t_b \rho_b , \\ K_1 &= \left(K_C^* + \epsilon_b J_1 \right) \left(K_Q^* T + K_B \right) . \end{aligned} \tag{5.46}$$

J_0, J_1 are defined by Eq. (5.45).

Following Eq. (2.19),

$$\begin{aligned} \mu &= \frac{C_V^2}{36\pi \, C_A^3} \\ &= \frac{\rho_a^2}{36\pi} \left[\frac{\theta^2}{(T+\theta)^2 \, (K_0 + K_1 \theta)^3} \right] . \end{aligned} \tag{5.47}$$

The value of θ that maximizes this expression is easily shown to be

$$\theta_1 = \frac{T_a}{6}\left[\sqrt{1+\frac{24K_o}{K_1T}} - 1\right] .$$

So, the optimum superheat for hot-air balloon operation, θ_{opt}, is

$$\theta_{opt} = \theta_1 \text{ or } \theta_s ,$$

whichever is larger. (If θ_1 should turn out to be smaller than θ_s, the balloon is optimally sun-powered.)

Once the optimum operating temperature is determined, μ can be calculated by Eq. (5.47). Then from (μm_p), Fig. 1 gives ζ, and the balloon radius is readily found from the reduced radius, $r(1-\zeta) = \frac{3C_A}{C_V}$. The intrinsic efficiency $\frac{m_p}{m_L} = \zeta$.

SEMI-QUANTITATIVE RESULTS

Numerical results depend upon values chosen for the large number of parameters required to describe the hot-air balloon system. Fairly well established are

K_Q = about 1.5×10^{-5} gm/cal (oxygen--hydrocarbons)
$K_c = 1.0 - 1.5 \times 10^{-5}$ cal cm^{-2}sec^{-1} (see Appendix A)

More uncertain are K_B and f_{BB}. Reasonable values might be $K_B = 0.1$ gm cal^{-1}sec, $f_{BB} = 2$. Balloon area density, $t_b\rho_b$, depends upon the fabric chosen and the maximum temperature it must withstand. For hot-air balloons operating at under 80°C, Mylar could be used, and 0.003 gm/cm^2 would be a reasonable value for the area density. For higher temperatures nylon laminates are required, which are substantially heavier (see Chapter VI).

A typical calculation for a Mylar hot-air balloon, operating at the optimum θ in the Mars lower atmosphere either at night or under other conditions where solar radiation is not absorbed, gives the following results for ζ and the "reduced radius" [$r(1-\zeta)$].

Duration, τ (min)	μ (kg^{-1})	Reduced radius $r(1-\zeta)$(meters)
1	0.2	4
10	0.02	8
100	0.0004	40

The intrinsic efficiency m_p/m_L, which in this case is equal to the parameter ζ, is a monotonically increasing function with (μm_p). The table above shows that intrinsic efficiency decreases rapidly with durations longer than several minutes -- correspondingly, the necessary balloon radius increases.

Although the actual numerical results depend upon particular parameter choices, the conclusion appears inescapable that the hot-air balloon for Mars is only practical if the flight is very short or if the balloon can be sun-powered. It may be well to point out explicitly why hot-air balloon experience on Earth cannot be carried over directly to Mars. There are two important differences between Mars' atmosphere and Earth's that bear on the operation of hot-air balloons. One is that the lower atmosphere of Mars is less dense by at least a factor of 10 than is Earth's atmosphere at a similar altitude. A factor of 10 in density acts to reduce μ by a factor of 100, for similar air temperatures. The balloon must therefore be larger to be buoyant, which means a greater rate of heat loss. Moreover, Mars' atmosphere is deficient in oxygen; the mass of fuel plus oxidizer that must be carried on Mars is (including tankage) roughly four times the mass of fuel alone that would be required on Earth. This means that duration, if achieved by fuel combustion, is purchased at a high price.

THE SUN-POWERED HOT-AIR BALLOON

Mentioned earlier was the possibility of eliminating the fuel requirement (except perhaps during initial filling) and operating during the day at a superheat achieved entirely by radiative exchange with the environment. The method of achieving high equilibrium temperatures previously mentioned, by tailoring the radiation properties of the balloon fabric, may not be the best way. Sunlight could probably be trapped efficiently by using a multi-layer balloon, the outermost layer transparent to solar radiation, but absorbing in the infrared, then within this envelope one or more layers of other fabrics to absorb the incident sunlight. (The inner layers would have openings to allow air circulation.) The analysis of such a "greenhouse balloon" has not been performed, but it might be worth exploring since a multilayer system would give greater flexibility -- and probably higher superheats -- than the single-fabric model adopted here. It also seems possible that since the heating occurs <u>within</u> the outer envelope, the circulation of the air inside could be inhibited so that the temperature of the outermost fabric layer, the outer skin of the balloon, would be reduced with a corresponding lower rate of heat loss to the outside air.

Even with a balloon whose heating is mainly derived from the sun, during flights lasting more than several minutes it would probably still be desirable to have the ability to add heat occasionally by means of a burner to make up for unexpected buoyancy changes. Buoyancy would decrease, for example, if the balloon drifted over new ground that had a lower emissive power, if haze in the atmosphere reduced the effective solar constant, or if the ambient air temperature rose. Of course, at nightfall or if an extended cloud passed between the balloon and the sun, the flight would be over.

Even if effective solar heating can be achieved, it would be desirable to use a heater to warm the air initially at the time the balloon is filled. Such a practice would have the advantage both of speeding the launch and, in the case of a surface launch, of providing greater lift near the surface. Since the air temperature in the low atmosphere during the day is highest near the surface, this is the point where buoyancy is most difficult to achieve.

For sun-powered hot-air balloons,

$$C_V = \frac{\rho\,\theta_s}{T + \theta_s} ,$$

$$C_A = \rho_b t_b .$$

If a multi-layer "greenhouse" balloon is used, C_A would be a summation over all the films together.

Again, assuming a fabric area density of 0.003 gm/cm^2 for the balloon fabric, the following table gives some typical calculated performance characteristics for a sun-powered hot-air balloon operating in the Martian atmosphere near the surface.

θ_s (°C)	μ (kg^{-1})	$r(1-\zeta)$ (meters)
20°	0.01	15
50°	0.06	7
100°	0.17	4

Contrast the 0.0015-cm thick superpressure balloon illustrated in Fig. 5. For that balloon μ = 2 kg^{-1}, $r(1-\zeta)$ = 1.1 m.

At this time the practicality of the sun-powered balloon remains to be proved. But it appears to be an interesting possibility, and merits more detailed investigation.

GENERAL REMARKS

The hot-air balloon is intrinsically far less efficient than the buoyant-gas balloon, so it must be larger in size to carry the same payload. The larger size increases launching problems, if the balloon is to be launched from the ground. A possible variation would be to fill the envelope by allowing air to flow in during the initial descent of the instrument package through the Mars atmosphere. This method has the advantage of eliminating the mass of a special blower, and it also keeps the balloon fabric away from the ground and its hazards. It obviously limits the applications and flexibility of the system, however.

Another disadvantage of the hot-air balloon is that, unless heat losses are partially or entirely made up by absorption of solar energy, only very short-duration flights are feasible on Mars. Flights longer than a few minutes entail hopelessly inefficient balloon designs. Unfortunately, the sun-powered hot-air balloon, if indeed it is a workable idea, will be very sensitive to changes in the radiation environment and in the ambient air temperature.

REFERENCES FOR CHAPTER V

5.1 Middleton, W. E. K., Meteorological Instruments, The University of Toronto Press, Toronto, Canada, 1941.

5.2 Schilling, G. F., Limiting Model Atmospheres of Mars, The RAND Corporation, R-402-JPL, August 1962.

5.3 Raven Industries, Inc., Test Results From a Demonstration of a System for Mid-Air Recovery, revised January 16, 1962.

VI. BALLOON FABRICS

In earlier chapters of this report the theoretical aspects of balloon operation were examined, and it was found that the performance of a balloon both directly and indirectly depends upon the characteristics of the balloon fabric. Physical properties such as thickness, density, tensile strength, and radiative emissivity have already appeared in our analysis; but there are other important properties that must be considered. For example, a fabric chosen must survive storage for many months under the conditions of deep space: e.g., possible temperature extremes and high fluxes of energetic particles. Then having withstood these conditions, it must perform reliably in an atmosphere that may have unfavorable characteristics: ozone in trace amounts, high UV intensities, and lower temperatures than are found in our own atmosphere.

In this chapter, a number of balloon fabrics currently available or under development are discussed. The parameters that determine the fabric's suitability for our purpose are given where they are known. Since none of the currently available balloon fabrics is ideal, we conclude the chapter with some suggestions for useful research in balloon fabrics.

PARAMETERS TO BE CONSIDERED

Mechanical Parameters

The general physical characteristics of a fabric are of prime importance in evaluating its suitability for balloon use. Here they are discussed in some detail.

Radiation Absorption

As was indicated in the chapter on the theory of balloons, the temperature of the gas in the balloon strongly influences the performance characteristics of any given balloon system, including final altitude of floating, stability in altitude, and duration of flight, among others. The equilibrium gas temperature is a strong function of the absorption and emission characteristics of the fabric in various portions of the electromagnetic spectrum. In this chapter the absorption characteristics (when available) of a given material are indicated for the ultraviolet, the visible, and the infrared portions of the spectrum.

Environmental-Problem Parameters

Chemical. Because many fabric materials are deleteriously affected by atmospheric gases such as ozone and water vapor, it is necessary to examine the fabric with these effects in mind. Water vapor exists only in trace amounts in the Martian atmosphere, and hence, some fabrics may be suitable whose only disadvantage is the deleterious action of this gas.

Radiation distribution. It is necessary to indicate the effect of ionizing radiation and ultraviolet radiation on the mechanical properties of the fabrics. The former is a hazard during the long flight to Mars; an intense flux of ionizing particles may be encountered along the way, and it is possible that the hull of the spacecraft will not suffice to protect the fabric. Ultraviolet radiation must be considered, because although the intensity of solar radiation at the top of the Martian atmosphere is only half the intensity reaching Earth's, the Martian atmosphere may permit a significant flux of ultraviolet to penetrate to lower altitudes.

Temperature. Because of the low temperatures expected on Mars, and the possibly high temperatures in transit and re-entry, it is necessary to know the temperature range over which the fabric maintains its integrity. Further it is important to know the effect of possible transient peaks in the temperature beyond this range, and the capability of the fabric for recovery.

Other Problems

Storage. Since balloons will have to be in space for periods approaching a year, it is necessary to determine whether such storage times reduce the reliability of the balloon.

Abrasion. Despite all precautions, during many phases of this mission a balloon may be subjected to considerable chafing. Hence, it is necessary to know how much abrasive action the fabric can withstand.

Minimum and maximum thickness. While it is certainly advantageous to minimize the total mass of fabric in a balloon, it is clear that structural integrity sets a minimum thickness on a given fabric. Similarly, although large superpressure balloons demand thicker material, there is a maximum thickness beyond which the fabric cannot be formed successfully into a balloon.

Manufacturing problems. Although many balloon materials may meet all other criteria and thereby constitute an attractive choice, it is necessary to know whether difficulties during fabrication reduce the reliability of the finished balloon.

Sterilization of fabric. The problem of contamination of the planet Mars by inadvertently carrying viable microorganisms from Earth has been widely discussed. It is likely that, throughout all phases of Mars exploration, scrupulous standards of sterilization will be required. Since the most effective sterilization procedures include heat soaking at a temperature of $120^{\circ}C$—$150^{\circ}C$, an important consideration is the balloon film's ability to withstand this treatment. For example, Mylar, the material most frequently mentioned in this report, as currently available, probably cannot be subjected to the heat soaking without weakening of the seams and deformation of the material.* It may, therefore, be necessary to seek some other form of sterilization — perhaps by chemical means, as by soaking the material in ethylene oxide.

No solution to the sterilization problem can be given now, but it clearly is an area for research before balloons can be used safely in Mars' atmosphere.

---

*FEP-Fluorocarbon does not have this disadvantage; see Table 3.

STUDIES OF FABRICS FOR BALLOON USE

Although balloons have been available for research use for many years, it is surprising how little information has been developed on possible fabrics and their characteristics. This is not to say that each developer of a balloon material has not tested his product to determine the basic mechanical characteristics, but rather that essentially none of the materials have been tested with regard to all the criteria discussed above.

For extensible balloons, only two fabrics have been used in this country — rubber and neoprene — and although their basic characteristics are to be found in any good chemical handbook, such items as the problems encountered in manufacturing balloons go unmentioned because they have been lumped in the general category of "manufacturing secrets."

For nonextensible balloon fabrics, two programs have been conducted in the past decade, which attempt to determine some of the characteristics of currently used lightweight plastic films. The first of these programs was part of a general balloon-research project conducted at the University of Minnesota, Physics Department,[6.1] between 1951 and 1955 under an Army, Navy, and Air Force contract. As part of this project, polyethylene and Mylar were considered (the latter material being a polyester developed by DuPont).

The second program was specifically one on balloon fabrics conducted by General Mills, Inc.,[6.2] under an Air Force contract between 1955 and 1958. On this project, once again, the emphasis was on polyethylene and Mylar, primarily because these materials had proved so useful. Some extremely limited investigation was conducted on other possible fabrics.

Specifically for high-temperature hot-air balloons, two relatively lightweight fabrics have recently been tested by Raven Industries.[6.3] These two are an acrylic-coated rip-stop nylon, and Mylar-laminated rip-stop nylon. As yet only limited tests have been run on these fabrics, but they represent the only consideration that has been given to hot-air balloon materials in this country for the past sixty years. (For hot-air balloons operating at moderate temperatures ($<80^{\circ}C$), special fabrics may be unnecessary.)

A TABULATION OF PARAMETERS

In Table 3 are listed the fabrics mentioned above (rubber, neoprene, Mylar, polyethylene, and the special hot-air fabrics) that have been used successfully for balloons on Earth. We have also included available information on FEP-Fluorocarbon, a "nonextensible" plastic that appears to offer certain important advantages. It is unaffected by solar ultraviolet and has a very wide temperature range. It might be an ideal material for hot-air balloons, or for equal-pressure buoyant-gas balloons, although its relatively high density constitutes a minor drawback.

As will be noted, Table 3 is characterized by a poverty of data that would permit an intelligent choice of a reliable fabric for a Martian balloon. It is obvious that because of this scarcity of useful information, any project to develop a Mars balloon must include a materials-research program to evaluate and choose the best balloon fabric for the purpose desired.

It should be pointed out that those values of "elongation to break" for plastic fabrics quoted in Table 3 may be misleading. Many of the nonextensible materials show an elongation-to-break approaching — and in some cases even exceeding — the percentage of elongation of extensible materials. It should be noted, however, that in the plastic nonextensible materials, these elongations refer to a test situation where the stress has been well beyond the elastic limit of the materials; and in many cases, the plastic has actually undergone some flow. The stress applied to these materials when used as balloons is well below that which will produce such elongations. In balloon operations the material is never purposely stressed beyond the region where Hooke's Law applies. Hence, the actual elongation undergone by the nonextensible balloon is generally only a few percent at most.

Table 4 gives information on the effects of UV radiation on representative plastics. [This problem can sometimes be alleviated by coatings or admixture of UV absorbing substances.[6.4]]

GENERAL REMARKS

For extensible balloons the only currently available materials are rubber and neoprene. Unfortunately, both have serious drawbacks.

REFERENCES FOR TABLE 3

a. Handbook of Chemistry and Physics, C. D. Hodgman (ed.), Chemical Rubber Publishing Company, Cleveland, Ohio, 1954.

b. Middleton, W. E. K., Meteorological Instruments, University of Toronto Press, Toronto, Canada, 1947.

c. General Mills, Inc., Mechanical Division, Balloon Barrier Materials, Final Report, AFCRC-TR-58-211 (DDC No. AD-152504), 1958.

d. University of Minnesota Physics Department, Reports on Research and Development in the Field of High Altitude Plastic Balloons, Contract NONR-710(01), DDC No. AD-75998.

e. Raven Industries, Inc., personal communication.

f. DuPont and Company, Inc., personal communication.

g. E. I. DuPont de Nemours and Company, Inc., Technical Report on DuPont Mylar Polyester Film, Film Department, Wilmington, Delaware, August 1956.

h. Modern Plastics Encyclopedia, Part I: Thermoplastics, Plastics Property Chart, 1963.

i. Peasley, J. A., Test of Two Hot Air Balloon Materials, Raven Industries Technical Note 30, 29 August 1962.

A

B

Table 3

THE CHARACTERISTICS OF EIGHT BALLOON FABRICS

	EXTENSIBLE		NONEXTENSIBLE					
			PRESENTLY—USED FABRICS					NEW FABRIC
			LIGHT GAS			HOT—AIR		LIGHT GAS or HOT—AIR
Characteristic	Natural Rubber	Neoprene (Polychloroprene)	Mylar (A DuPont Polyester)	Weatherable Mylar	Polyethylene	Acrylic-Coated Rip-Stop Nylon Fabric	.35 mil Mylar Laminated to Rip-Stop Nylon	FEP—Fluorocarbon
Density (gm/cm^3)	.92 — .96	1.25	1.4	1.4	.95	~1	~1	2.15
Tensile Strength (atm)	230 — 315	245	~1400	~1400	~270	~900	~1500	~130
Thermal Conductivity (10^{-4} cal sec^{-1} cm^{-1} $°C^{-1}$)	(25°C — 100°C) 5.0	(25°C — 100°C) 4.6	3.63	3.63	11 — 12.4	1 — 10	3.0 — 5.8	unavailable
Elongation at Break (%)	(at 25°C) 470 — 600	(at 25°C) 580	for .0025 cm thickness, 30 — 130	for .0025 cm thickness, 70 — >200	for .005 cm thickness, 20	~20	~20	300
Gas Permeability (std cc-cm cm^{-2} 1 atm^{-1} sec^{-1})	(for H_2) 5.3×10^{-8} — 3.6×10^{-7} (for air) 8.35×10^{-8}	(for H_2) 8.35×10^{-8}	(for H_2, + 26.2°C) 1.5×10^{-11} (for He, - 78.5°C) 4.4×10^{-13} (for N_2, + 25°C) 2.29×10^{-11}		(for H_2) 8.9×10^{-8} (for He) 4.95×10^{-8} (for N_2) 2.06×10^{-9} all at 25°C	unavailable	unavailable (but probably equivalent to Mylar)	CO_2 1.7×10^{-10} N_2 1.7×10^{-10} H_2 1.2×10^{-9}
Radiation Absorption Characteristics	opaque	opaque	strong in UV (~.2 — .315μ); transparent in visible and near IR (.315 — 5.1μ); strong in far IR (5.1 — 14.3μ)	same as Mylar except in UV where strongly absorbing from ~.2 — .41μ, and weak band in IR (3.2 — 3.3μ)	moderate to weak in UV (.2 — .315μ); very transparent in visible; strong band in near IR (~3.3 — ~3.7μ); moderate to very weak in far IR (5 — 14μ)	unavailable	unavailable (but must have absorption characteristics of Mylar plus nylon)	transmits more UV, visible, and IR radiation than window glass; no absorption bands in region of maximum solar radiation
Temperature Range in Which Material Remains Useful (deg C) Maximum	>100	>100	~80	~80	~50	>120	>120	~220
Minimum	stiffening point, -47 brittle point, -23 — -54	s. p., -37 b. p., -40	<-195	<-195	-70 to -80 (brittle)	<-80	<-80	~-250
Chemical Effects Exposure to ozone	deteriorates	deteriorates	degraded somewhat by exposure; tensile strength 30% down after long exposure to mixture of air and 3.3% ozone	somewhat better than Mylar because of coating	somewhat better than Mylar	unavailable	unavailable (but must have some characteristics of Mylar)	does not appear to "weather" after 5 years outdoor exposure
Exposure to water vapor	unaffected	unaffected	unaffected	unaffected	unaffected	unavailable	slight — none	unaffected
Radiation Exposure Effects UV radiation	deteriorates	deteriorates severely	significant decrease in effect at lower temperatures; see Table 4	decrease in effect due to coating which absorbs UV	See Table 4	slight	slight	unaffected after 6100 hours high-intensity UV environment at temperatures >55°C
Ionizing radiation	unavailable	unavailable	mechanical properties unaffected up to dosage of 10^8 rad	should be the same as regular Mylar	unavailable	unavailable	unavailable	unavailable
Storage	apparently can be safely stored for long periods	can be safely stored for long periods	long-term storage does not seem to affect the mechanical properties, nor does creasing in packing		same as for Mylar	unavailable	unavailable	unavailable
Abrasion Resistance	excellent; tear resistance, 125 kg/cm	excellent; tear resistance, 75 kg/cm	fair abrasion resistance if thicker than .001 cm; tear strength (.0025 cm thick fabric) 15 gms; cannot be subjected to abrasive surface		moderate resistance if thicker than .001 cm; tear strength ~175 gms; cannot be subjected to abrasive surface	unavailable	unavailable	tear strength 125 gm (pull required to continue tear in 1 mil sheet after starting)
Thickness Range for Balloon Use (cm)	unknown maximum thickness; bursting thickness of 10^{-3} cm implies uninflated thickness of ~.036 cm	unknown max thickness; b. t. of $.5 \times 10^{-3}$ cm implies u. t. of ~.02 cm	minimum ~.001 maximum ~.005	minimum to date ~.001 maximum ~.005	minimum ~.001 maximum >.01	.008 cm used to date	.008 cm used to date	minimum ~.001 cm
Manufacturing Problems	manufactured by dipping or molding; size attainable by dipping limited; difficulty in obtaining uniform thicknesses by either method; may be a limitation on size		requires good quality control to preclude all pin holes; hard to seal—need glues, polymers, tapes, etc. that may degrade differently from the fabric; fabric has low capability of plastic flow, so it must be perfectly aligned before sealing; any misalignment can be a point of weakness, hence of failure		requires good quality control to avoid pin holes and to assure fabric with good low-temperature characteristics; can be heat sealed	sealed by sewing fabric; seals have 50% of tensile strength of fabric	sealed by sewing fabric; seals have 50% of tensile strength of fabric	Type A cannot be adhesive-bonded but can be heat-bonded; Type C can be adhesive-bonded
Remarks	good for short-term uses where effects of ozone and UV will not play major role and where temperatures not too low	short-term uses (vertical balloons); UV resistance can be increased by heat-aging just before launching (100°C)	long successfully used on Earth despite its disadvantages; used successfully for super-pressure application; major disadvantages are effects of UV and ozone	because of resistance to UV and possible ozone, offers good possible substitute for regular Mylar; is somewhat heavier than regular Mylar	long used successfully for balloons; not suitable for super-pressure balloon; deteriorates under UV and with exposure to ozone	appears useful for hot-air application; needs more tests vs. UV and ozone	appears to be useful for hot-air, but heavier than acrylic-coated nylon and may deteriorate more under UV and ozone because of Mylar; needs more tests	potentially excellent for equal-pressure and hot-air balloons; free of pinholes; good radiative characteristics; warrants further study
References	a, b	a, b	c, d, e, f, g	c, e, f	a, c, e, f, h	e, i	e, i	h

Table 4

EFFECT OF ULTRAVIOLET RADIATION ON FOUR BALLOON MATERIALS[6.5]

Variation in the decrease of tensile strength according to material, length of exposure, and environment (nitrogen versus vacuum). Source of radiation, monochromatic mercury arc lamp (G.E. 630T8) at 0.2537 μ. Materials were exposed at room temperature.

Length of irradiation (hours)	Decrease in tensile strength (per cent) for material specified in environment specified							
	Mylar		Polyethylene		Nylon		Acrylon	
	N_2	Vacuum	N_2	Vacuum	N_2	Vacuum	N_2	Vacuum
30	18	(6)*	7	(7)*	7	3.5	(1.5)*	(3)*
60	26	(3)*	59	12	15	9.5	10	5
90	34	2	65	25	25	12	23	15
120	38	9	70	34	37	16	27	17
150	40	15	73	38	46	18	30	18
Remarks	Ref. c indicates that Mylar becomes brittle at -70°C after exposure to >0.05 watt-hr/cm² UV radiation at 0.312 — 0.332 μ. It also indicates that deterioration is less when exposure occurs at lower temps		Becomes brittle at room temp. after long exposure		Surface becomes gummy after exposure.			

*Percentages in parentheses represent minus values — i.e., an improvement in tensile strength.

There is a conspicuous need for a material that can withstand (1) low temperature (of the order of $-100^{\circ}C$) and (2) ultraviolet radiation. For this reason other materials that have not thus far been considered for balloons should be investigated. (An example of such a rubber-like material is the "inorganic rubber" phosphonitrilic chloride.)

For the equal-pressure balloon (and the hot-air balloon), the yet untested material FEP-fluorocarbon appears to have many advantages. It is always possible, however, that manufacturing problems or other difficulties would preclude its use for balloons. Polyethylene, the favorite terrestrial balloon film, probably has too limited a temperature range for use on Mars, and it deteriorates under UV irradiation.

Mylar with its shortcomings appears to be the only current choice for the superpressure balloon. For this balloon, it would be desirable to develop a material with high tensile strength that can withstand both high temperatures (for sterilization) and solar UV. No readily available film appears to surpass Mylar, but with modifications certain plastics might serve. For example, Cellulose Triacetate has the one disadvantage of being very permeable to gases; otherwise, its characteristics appear quite favorable—perhaps it could be coated to render it impermeable. Nylon (HT-1, a high temperature modification) is fairly strong and has an adequate resistance to high temperatures. However, its quoted lower-temperature limit is only $-50^{\circ}C$ and its resistance to UV is not outstanding. Polyurethane films, although not quite as strong as Mylar, have a wide temperature tolerance and resist environmental deterioration. They have not yet, however, been extensively studied.[6.6] Clearly the superpressure-balloon fabric problem merits further investigation, since no currently available fabric fulfills all of the requirements.

REFERENCES FOR CHAPTER VI

6.1 University of Minnesota Physics Department, Reports on Research and Development in the Field of High Altitude Plastic Balloons, Contract NONR-710(01), DDC No. AD-75998.

6.2 General Mills, Inc., Mechanical Division, Balloon Barrier Materials, Final Report, AFCRC-TR-58-211 (DDC No. AD-152504), 1958.

6.3 Raven Industries, Inc., personal communication.

6.4 Strobel, A. F., and M. R. Leibowitz, "Ultra-Violet Absorbers," Modern Plastics Encyclopedia Issue for 1963, Vol. 40, No. 1A, September 1962, pp. 497-501.

6.5 Stephenson, C. V., B. C. Moses, and W. S. Wilcox, "Ultra Violet Irradiation of Plastics. I. Degradation of Physical Properties," J. Polymer Sci., Vol. 55, 1961, pp. 451-464.

6.6 Modern Plastics Encyclopedia, Part I: Thermoplastics, Plastics Property Chart, 1963.

VII. OTHER NECESSARY ELEMENTS IN BALLOON-SYSTEM DESIGN

The choices of buoyant gas, balloon types, and balloon fabrics have all been discussed in preceding chapters. Other elements that enter into the design of the total balloon system are discussed in this chapter: launching methods, methods for locating the floating balloon, and such design questions as the balloon shape and how loads are carried.

Launching Methods

In this section we consider possible launching methods in view of the uncertainties of Martian conditions and the peculiarities of balloon systems.

The prevalent procedure for launching nonextensible light-gas balloons on Earth is as follows: The balloon is unfolded, is partially inflated, is allowed to assume a fully extended position vertically over the payload, and then is released. The balloon, being rather fragile, can easily be destroyed if it is subjected to large forces while restrained. Part of the balloon is slack when it leaves the ground (and hence presents a large potential sail area to the wind), and this portion is most vulnerable to the wind in the moments just before launching. For this reason, a practical limit has been set on the maximum wind velocity in which one should attempt to launch a nonextensible balloon.* This limit is 15 knots.[7.1]

---

*We are here describing the launching problems of a nonextensible balloon, but the same problems apply to one composed of an extensible fabric, although, as such a balloon is generally launched in a taut state, those problems are not quite so severe.

Many methods have been suggested and tried for protecting balloons from high winds. In some, the partially inflated balloons are sheltered under covers of various sorts or behind windscreens. Other attempts have employed the technique of "reefing" or squeezing together the unfilled portion of the balloon to decrease the area exposed to the wind and thus minimize the tendency for this portion to act as a sail. Most of these methods have been successful to one degree or another. They have pointed to two basic principles for increasing the reliability of a balloon launching:

1. the smaller the balloon area exposed to the wind, the greater the probability of a successful launching;
2. the shorter the period that the balloon is exposed to the wind in a restrained state, the greater the probability of a successful launching.

Let us examine the problem of launching a balloon from the surface of Mars in the light of these two principles.

LAUNCHING FROM THE SURFACE OF MARS

No matter how extensive our information on the surface conditions on Mars before the landing of the balloon-bearing capsule, two uncertainties will remain:

(1) There will be uncertainty in our ability to predict the wind vector -- even for a very short forecast period.

(2) There will be uncertainty in our knowledge of the specific topography of the actual landing point.

Conditon (1) suggests that we cannot be confident that winds will not be hazardous during inflation unless shelter is provided. Condition (2) suggests that even if the winds were predictable,* the topography

---

*The wind force on a balloon is proportional to (among other parameters) the atmospheric density and the wind velocity squared. While it is true that the atmospheric density at the surface of Mars is about 0.1 of that at sea level, Earth,(7.2) the uncertainty in the wind velocity as expressed above negates this potential reduction in the wind hazard.

(rock outcroppings, etc.) makes inflation hazardous unless the balloon is sheltered. If the gas-generation rate were slow, these hazards would be magnified.

The experience of balloon users on Earth and the two principles for increasing the reliability cited above are a guide to the design of a balloon inflation method suited to the uncertain environment of Mars.

Figure 7 suggests such a method. In part (a) of the figure, the capsule has landed (and righted itself, if necessary). In the upper portion of the capsule is a padded compartment in which the balloon is so folded as to permit gas of the necessary volume to enter the <u>upper</u> part of the balloon without disturbing the unfilled lower portion. Attached to the balloon is the coiled load line, and to it, the payload. Deeper in the capsule is the gas-generation or -storage unit, connected (by a hose that can be disconnected and sealed) to the upper portion of the balloon. After the protective cover (for atmospheric entry) has been removed, the balloon compartment remains protected from the Martian surface by a flexible membrane that is geometrically expandable -- possibly by having been spirally pleated in packing. It is visualized that the protective membrane* will fold out as the balloon inflates. In the balloon compartment the pressure is the same as the atmospheric pressure at the surface of Mars.

Part (b) of Fig. 7 illustrates the balloon inflated with the gas required to accomplish its mission, the membrane fully expanded but still enveloping the upper part of the balloon, acting as a buffer between it and the atmosphere. In this configuration the balloon is protected from possible abrading wind-blown debris, and the slack portion of the balloon is not a target for the wind. Within limits, it can be held in this configuration for launching when desired. Also, within limits, this launching system permits

---

*A material suitable for the membrane might be a somewhat thicker sheet of the plastic material used for the nonextensible balloon.

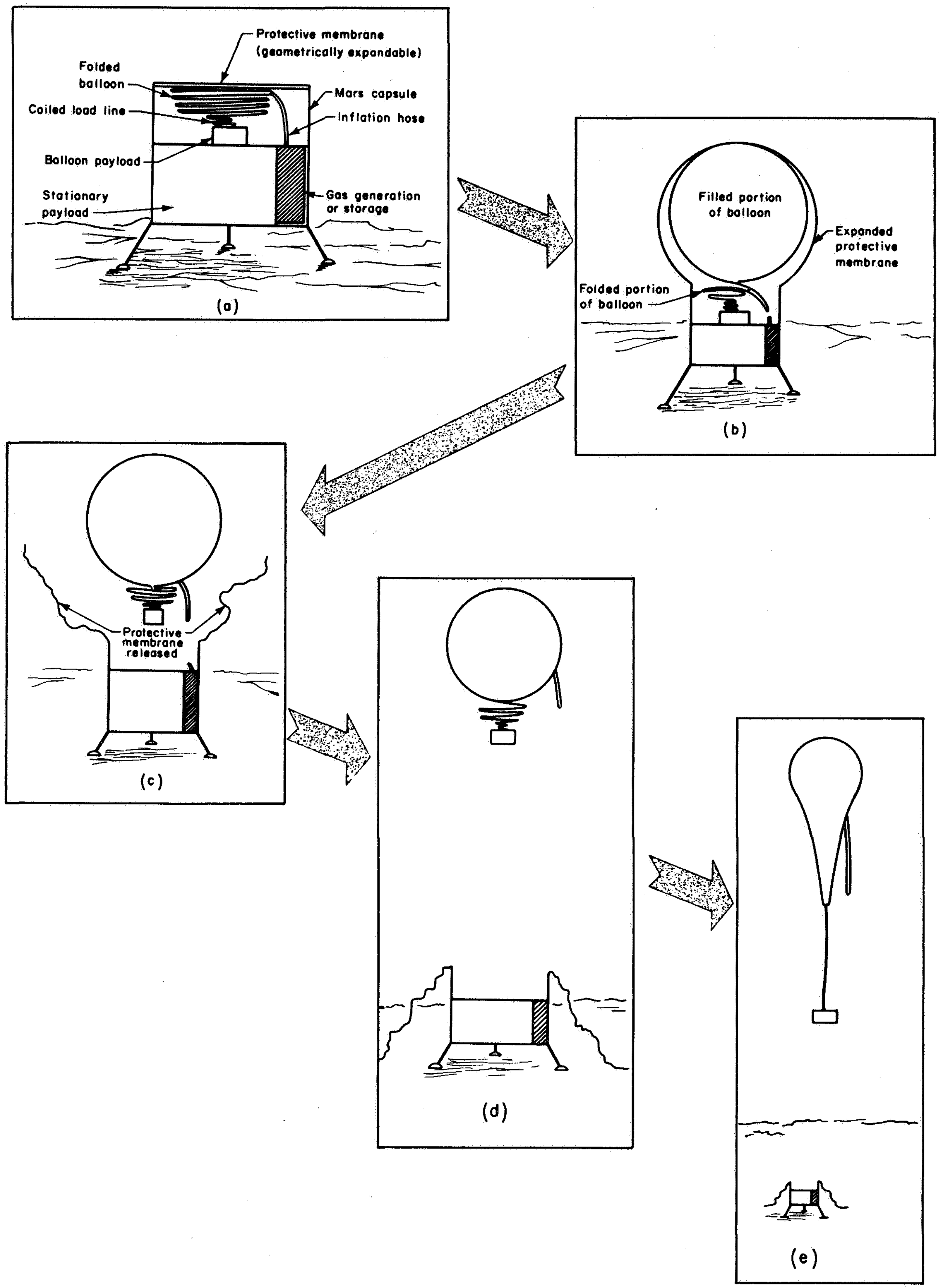

Fig. 7 — Conceptual drawing of Martian ground launch: (a) package ready for activation; (b) balloon protected during inflation; (c) release; (d) unextended rise; (e) extended rise

a rather wide latitude of acceptable gas-generation rates. Part (c) shows the membrane collapsed and the balloon rising above the capsule. Part (d) shows the balloon at a somewhat greater altitude. It will be noted that both the unfilled part of the balloon and the load line are still folded, and the payload is held tightly under the filled portion of the balloon. The retention of this compact configuration is an attempt to protect the balloon and payload during the initial moments of the launch. Of course, with the protected configuration, it is conceivable that the wind might be measured before the launch and the balloon kept under cover until safe conditions prevailed. Part (e) shows the balloon and load line both fully extended and rising in the Martian atmosphere.

While the method described is obviously for the case of the launch of a single balloon with a relatively small initial volume of gas, the same method may be applicable to a large number of small extensible balloons launched from a single location. In the latter case, the launching capsule might consist of many small cells, each containing one balloon and each covered by its expanding membrane. The gas could be supplied from individual sources or from a central system.

The method described is certainly not the only way of remotely launching a balloon from the surface under possibly hazardous conditions. It is felt, however, that this, or a similar system (although still needing engineering investigation) offers an uncomplicated and apparently reliable method of meeting the criteria for a remote surface launching.

When considering a hot-air balloon, it is apparent from Chapter V that such a balloon, while nonextensible, is completely filled before leaving the ground. If one is talking about a relatively small hot-air balloon, the method described above may still apply. In fact, if the protective cover is transparent in the visible, it is conceivable that, by daylight, the cover would be employed as a "greenhouse," and thereby solar energy could aid in heating the balloon air. If the balloon is large relative to the Mars capsule, it will be necessary either to inflate this balloon in the open with all the attendant hazards (noting of course that the wind can be measured before the inflation -- thereby allowing one to choose a time when the risks are somewhat reduced), or to inflate it in the air on the way down, as is discussed below.

THE AIR LAUNCHING OF BALLOONS ON MARS

Another method of contending with the uncertain environment at the surface of Mars is to avoid it completely by launching the balloon before the capsule lands. In a system that might accomplish this, a parachute is deployed, from which is suspended the main Mars capsule. The balloon and balloon payload are attached on top of the parachute [part (a) of Fig. 8]. When filled, the balloon and the payload are separated from the top of the parachute as in parts (b) and (c) of Fig. 8. There is no question that such a system will work;* the major questions concern its disadvantages and advantages in comparison to a surface-launching system.

One major disadvantage is contained in the general question of reliability; only in this case it may affect the reliability of the entire Mars mission because the balloon being inflated is in direct contact with the parachute of the main capsule. It is certainly conceivable that failure during inflation could damage the parachute and, hence, damage or destroy the main payload. Of course safety measures could be taken, but each would add another degree of complexity to the system. The balloon and its payload might be attached to its own parachute before inflation. This, however, would require that the gas or heat source be lowered with the balloon. The two parachutes, even though smaller, constitute a mass penalty that may not be offset by the elimination of the surface-launching equipment. One disadvantage of the pre-landing launch is that the time available for inflation is rather limited.

---

*The system described was actually developed by the U. S. Air Force[7.3] for the purpose of dropping balloon-carried payloads into the eye of a hurricane and having them float there for extended periods, providing analytical and tracking data.

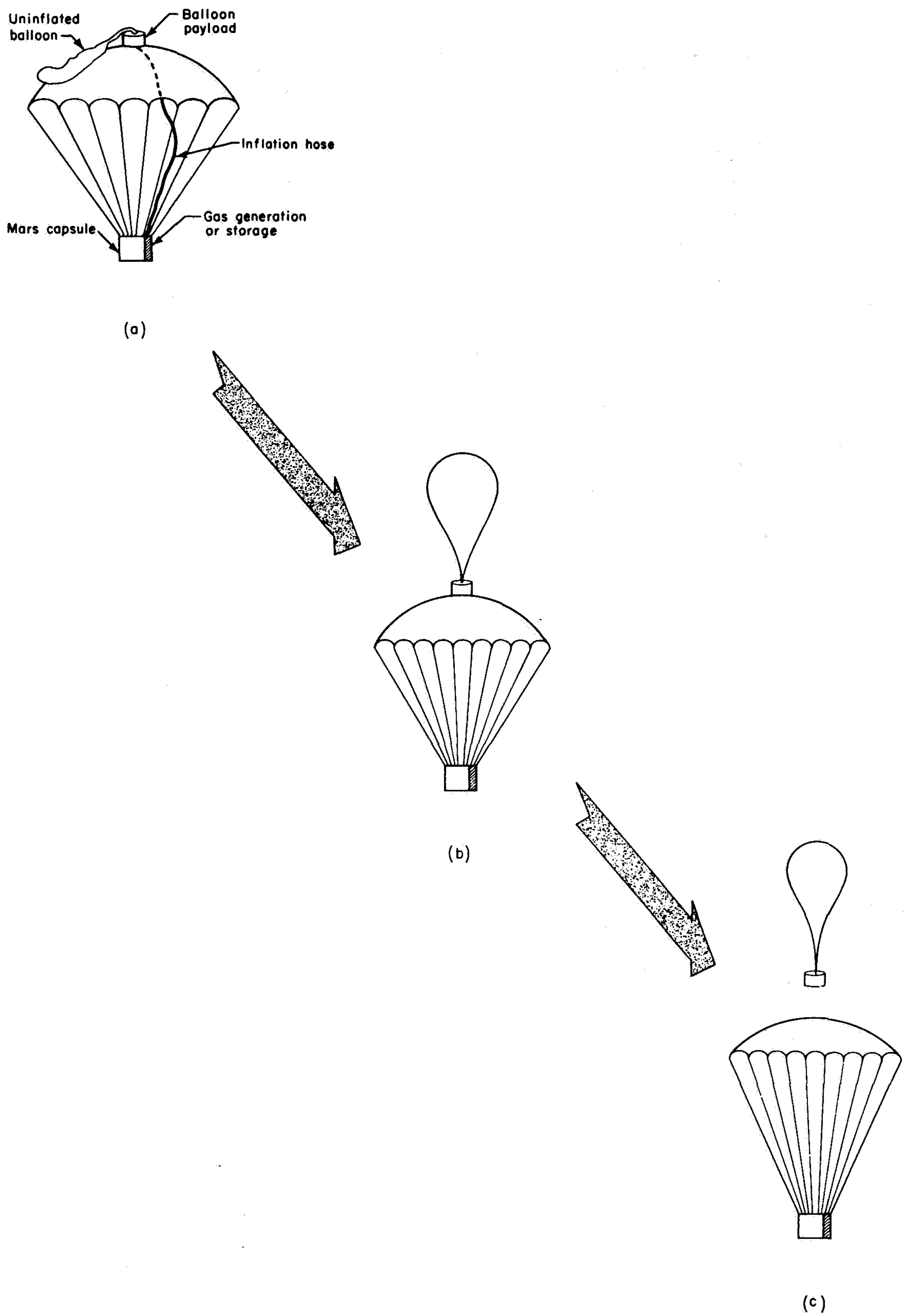

Fig. 8 — Conceptual drawing of Martian air launch during planetfall:
(s) deployment; (b) inflation; (c) separation

In the case of the light-gas balloon, the time limitation may restrict the choice of gas-supply devices to some that are troublesome to transport from Earth or that require a greater energy input; clearly, every demand for greater energy means less payload mass.

The advantage of the air-launching system may be obvious. Any truly reliable system of air launching a balloon during descent assures the safe arrival of one unit, whatever befalls the main capsule during landing; and this unit could, if desired, carry instruments capable of completing its mission independently of the main capsule and communicating the results to Earth. At the very least, as stated in the beginning, the air launch would avoid the uncertainty of surface conditions. A variant on the air-launching method described was suggested and has actually been tried by one of the balloon-design groups.[7.4] In this technique, if applied to our problem, the fall of the entry capsule deploying the balloon would be slowed, and the balloon filled as it streams behind the re-entry body. To date this method has been tested at relatively low velocities, and it remains to be shown that it will work equally well at the higher velocities but lower densities that might be encountered in the Martian atmosphere. If successful, such a method has the obvious advantage of not requiring the extra mass of a special parachute for the balloon. It does suffer, however, from the disadvantage of allowing only a relatively short time for the gas-generation system to complete its task. Certainly it appears that the potential net advantage of such a method warrants further research.

In summary then, it appears conceptually possible to provide both a surface-launching system and an air-launching system. Each has its own degree of reliability and foreseeable advantages and disadvantages. It is not possible, at this stage of the consideration of a Mars balloon system, to determine uniquely which method offers the most promise of successful mission; it <u>is</u> possible to determine only that methods worthy of further study do exist.

Position-Finding Methods

Many of the experiments suggested in Chapter II require determinations of the balloon's three-dimensional position during its flight. Its altitude must be known if geophysical measurements are to be interpreted and if observations of surface features are to be scaled. Moreover, the value of the exploration of the surface is greatly enhanced by knowing where on the planet the observations were made.

There are three classes of position-finding systems: (1) self-contained on the balloon, (2) stationed entirely at the "home base," and (3) interacting. The problem of determining the location of an instrumented capsule placed on the planet exists for any mission that soft-lands instruments. It will not, therefore, be discussed at length here. There are many position-finding methods that might be considered for balloons. A number are discussed qualitatively in the remainder of this section.

Areographical Position

All instruments on the balloon. The measurement of time and solar elevation at the balloon's position serves to locate it on a circle around the sub-solar point. Three or more such measurements during a day would define the location if the balloon were stationary.

If an artificial satellite has been put into orbit around the planet, measurements on the balloon of the doppler effect in the satellite's radio signal will locate the balloon's position. Ambiguities in this determination could be resolved by combining this method with a rough measurement of the solar elevation angle.

Transmitter only on the balloon. The line-of-direction from the home base to the balloon could be determined by means of a direction-finding antenna at the home base; and the balloon's velocity away from the base could be measured by the doppler shift of its radio signal. These two measurements would approximately indicate the balloon's course. Since the width of an antenna beam increases with distance, the inaccuracy of an angular measurement increases as the balloon drifts away from the home base.

If two receivers near the home base were separated by a long base line and the balloon transmitted a modulated signal, the difference of arrival time of the signal at the two receivers would serve to place the balloon on a hyperbola. Of course, both the length and direction of the base line must be accurately known and the balloon's path must make an appreciable angle with the baseline.

Two-way systems. The range of the balloon can be accurately determined by a pulse-transponder system. A variation on pulse transponding is two-way doppler, a system much used for missile tracking. Both systems are familiar in military applications.

Altitude

Using atmospheric measurements. When the temporal (and spatial) variation of pressure with altitude is known, altitude can be approximately determined on Mars, just as on Earth, using an aneroid barometer calibrated for Mars. Any other atmospheric parameter found to be a relatively constant function of altitude could be used equally well.

Tracking during balloon launch. If the balloon is launched from the surface, it rapidly reaches an approximately constant terminal velocity (see Appendix C). A nonextensible balloon will continue to rise until it reaches its floating altitude. If the winds are weak, this rise will be approximately vertical over the home base, so tracking during this phase of the flight, by doppler or transponder, will permit the floating altitude to be determined. The balloon in its flight may still vary in altitude, but this motion would be measurable from the balloon itself by barometric instruments.

Radio altimeter. All of the altimetric methods cited so far measure only the height above some standard level, not the height above the local surface. If payload limitations permitted, a small radio altimeter could be used to measure height above the surface very accurately. The instrument need not operate continuously.

Timing drops. In several of the experiments suggested in Chapter II, such objects as smoke bombs, explosive charges, or instruments are dropped from a balloon. If an object has a simple aerodynamic shape, as does a sphere, and the atmospheric parameters are known, the time it takes for the object to drop (measured on the balloon by some signal produced when the object reaches the surface) is a function of the local height of the balloon. Even if the object is parachuted, an approximation of altitude could be derived, although a crude one.

Balloon Configurations

Geometric balloon shape. Throughout the body of this report, in discussing the volume of gas, we have assumed that the balloon was spherical. While this assumption is adequate for the computation of performance, and agrees closely with reality in the case of the extensible balloon, it should be pointed out that the shape of a nonextensible balloon usually deviates considerably from a sphere. This deviation results from an attempt to design a balloon that is in the shape that a confined bubble of gas tends to assume when a load is attached to the lower part of the envelope. It has been found that when a balloon is produced in the "natural shape," the longitudinal stresses across the seams (which are frequent causes of balloon failure) are almost completely eliminated. In its perfected form, the "natural-shape" balloon is flattened at the top, with the equatorial bulge in its upper portion, and then a gradual taper to the bottom where the load is attached. Additional information on this design may be found in several available publications.[7.1,7.5]

Load-carrying configurations. Normally, the payload of a balloon is suspended from beneath on a load line.* The length of the line depends on several considerations. Long load lines imperil the payload at launch in that they protract the post-launch period during which the payload is endangered by surface obstacles. Sometimes, however, the experiment to be conducted requires a clear field of view upward; then it is advantageous to hang the payload as far as possible below the balloon to minimize the apparent angular size of the obstruction to the field of view. Additionally, depending on the requirements of the experiments, the period of the payload's pendulum swing can

*The load is transferred to the balloon by means of a structure at its base. Normally this structure is a metal ring to which the balloon fabric is clamped and the load line attached.

be adjusted by lengthening or shortening this line. Obviously, these three considerations may lead to mutually inconsistent requirements for a particular payload. To alleviate this inconsistency, several novel methods have been perfected to meet the peculiar demands of a given instrument. In one, the sensing instrumentation requiring an unimpeded zenith look angle, is placed on top of the balloon, with a counterbalancing load suspended below. Although obviously the total mass of such a sensor is limited and such a mount presents some difficulties in launching, placement on top of the envelope provides an ideal position for such a sensor.

If it is desirable for the pendulum action of a suspended payload to be damped, the payload can be distributed along the load line. Properly designed, the resulting double or triple pendulum quickly damps out any tendency of the payload to swing. When, for one reason or another, a dangerously long load line must be used, the load line may be kept "snubbed" during the launch period and then, at a safe altitude, permitted to extend to full length.

The methods described above illustrate that there is considerable flexibility in the placement of payloads on balloons, with a consequent flexibility in the choice of experiment and launching environment.

REFERENCES FOR CHAPTER VII

7.1 Handbook of Geophysics, Geophysics Research Directorate, Air Force Cambridge Research Center, 1957.

7.2 de Vaucouleurs, G., Physics of the Planet Mars, The Macmillan Company, New York, 1954.

7.3 Payne, J. C., Final Report on the Hurricane Positioning Device Feasibility Study, Balloon Development Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, February 1960.

7.4 Powell, W. W., Final Technical Report on Air Launched Balloon Devices, Anderson, Greenwood and Company, AGCO Report 540, March 1961.

7.5 University of Minnesota Physics Department, Reports on Research and Development in the Field of High Altitude Plastic Balloons, Contract NONR-710(01), DDC No. AD-75998.

VIII. NUMERICAL EXAMPLES ILLUSTRATING THE CAPABILITIES OF BALLOONS

Given the discussion presented in the previous chapters, it is now possible to examine the capabilities of balloons in the light of specific examples. Rather than choosing entirely arbitrary examples, three were selected from among reasonable balloon missions, to illustrate the modes of balloon uses described in Chapter II. These examples are: (1) the extensible balloon as a vertically traveling sensor platform, (2) the superpressure balloon as a long-duration, horizontally traveling sensor platform, and (3) the equal-pressure balloon as a conveyance.*

The Extensible Balloon as a Vertically Traveling Sensor Platform

An extensible balloon has a short life, and its sampling coverage is roughly one-dimensional — upward from the launching area. For a minimal description of the atmosphere (which varies in time as well as three-dimensionally in space), a number of vertical passes are required. If we assume that a meteorologically significant time interval between samples is (as on Earth) several hours, ten vertical passes might be a satisfactory minimum.

For our example, then, we take a system of ten identical balloons and payloads that can be launched successively at significant intervals. We shall assume that we wish to measure certain standard meteorological

---

*Despite the potential value of the hot-air balloon as a conveyance, it was decided that, because its feasibility is uncertain, no numerical example would be included beyond what is presented in Chapter V.

parameters (such as pressure, temperature, and humidity), for which extremely light sensors have been or can be developed. Such measurements do not require long-range and wide-band telemetry or large amounts of power. Under these assumptions, we shall examine two possible payload masses, 0.1 kg and 1.0 kg for each balloon. To see the effect of the design maximum altitude on the system parameters, we shall choose two density altitudes that appear realistic; they are 5×10^{-5} and 1×10^{-5} gm/cm^3, corresponding roughly to 7—25 and 29—57 km (see Chapter III).

A summary of the findings is tabulated below. The analysis of the four cases, which will follow the methods of Chapters II and V, is spelled out following the table.

For a ten-balloon system to reach a density altitude of --	-- with a payload mass in each balloon of --	-- it requires a total mass lifted from Earth of about --	-- which occupies a volume on the spacecraft of about --
5×10^{-5} gm/cm^3	0.1 kg	11 kg	1.6×10^4 cm^3
	1.0 kg	63 kg	7.6×10^4 cm^3
1×10^{-5} gm/cm^3	0.1 kg	63 kg	8.2×10^4 cm^3
	1.0 kg	152 kg	19.0×10^4 cm^3

VERTICALLY RISING PLATFORM

Parameters Common to the Four Cases	Values	Notes*
Density of fabric (neoprene or rubber)	$\rho_b = 1$	(a)
Final thickness of fabric	$t_f = 10^{-3}$ cm	(a)
Factor of total stretchability	$q_f = 6$	(a)
Unstretched thickness of fabric	$t_u = 0.036$ cm	(a)
Balloon temperature parameter (assumed)	$\Lambda = 1.1$	
Acceleration parameter	$\lambda = 0.1$	(b)
Molecular-weight ratio	$\beta_0 = 14.5$	(c)
Gas-transport system's mass ratio	$m_g/m_t = 0.09$	(d)
Buoyant-gas lifting efficiency	$m_L/m = 0.92$	(c)
Payload density (assumed)	$\frac{m_p}{V_p} = 1.0$ gm cm^{-3}	
Gas-transport system's volume ratio	$\frac{V_t}{m_g} = 15.0$	(d)
Packing ratio of fabric	$f_p = 0.8$	(e)
Factor to allow for "extra mass"	$F = 2.0$	(f)
Factor relating to "back pressure" on material	$P_f = 1.0$	(g)

*Notes follow the four tables.

VERTICALLY RISING PLATFORM: CASE 1

Payload mass: 0.1 kg; density altitude: 5×10^{-5} gm/cm^3		
Item	**Values**	**Notes**
Radius of unstretched balloon	r_u = 19 cm	(g)
Mass of fabric for each balloon	m_b = 0.17 kg	
Mass carried by each balloon (gas excluded)	m_L = 0.27 kg	
"Intrinsic balloon efficiency"	$\frac{m_p}{m_L}$ = 0.37	(h)
"Total mass efficiency"	m_p/m_T = 0.09	(h)
"Volumetric efficiency"	V_p/V_T = 0.06	(h)
Mass of buoyant gas for each balloon	m_g = 0.024 kg	(i)
Mass of gas-transport system (including gas generated), prorated for one balloon	m_t = 0.266 gm	
Volume of gas-transport system, prorated for one balloon	V_t = 360 cm^3	
Volume of each packed balloon	V_p = 340 cm^3	
Totals for ten-balloon system (including factor F)		
TOTAL MASS:	11.0 kg	
TOTAL VOLUME:	1.6×10^4 cm^3	

VERTICALLY RISING PLATFORM: CASE 2

Payload mass: 1.0 kg; density altitude: 5×10^{-5} gm/cm^3	
Item	**Value**
Radius of unstretched balloon	r_u = 35 cm
Mass of fabric for each balloon	m_b = 0.6 kg
Mass carried by each balloon (gas excluded)	m_L = 1.6 kg
"Intrinsic balloon efficiency"	$\frac{m_p}{m_L} = 0.636$
"Total mass efficiency"	$m_p/m_T = 0.16$
"Volumetric efficiency"	$V_p/V_T = 0.13$
Mass of buoyant gas for each balloon	m_g = 0.14 kg
Mass of gas-transport system (including gas generated), prorated for one balloon	m_t = 1.55 kg
Volume of gas-transport system, prorated for one balloon	V_t = 2,100 cm^3
Volume of each packed balloon	V_p = 710 cm^3
Totals for a ten-balloon system (including factor F)	
TOTAL MASS:	63 kg
TOTAL VOLUME:	7.6×10^4 cm^3

VERTICALLY RISING PLATFORM: CASE 3

Payload mass: 0.1 kg; density altitude: 10^{-5} gm/cm^3	
Item	**Value**
Radius of unstretched balloon	r_u = 58 cm
Mass of fabric for each balloon	m_b = 1.5 kg
Mass carried by each balloon (excluding gas)	m_L = 1.6 kg
"Intrinsic balloon efficiency"	$\frac{m_p}{m_L}$ = 0.061
"Total mass efficiency"	m_p/m_T = 0.016
"Volumetric efficiency"	V_p/V_T = 0.012
Mass of buoyant gas for each balloon	m_g = 0.14 kg
Mass of gas-transport system (including gas generated), prorated for one balloon	m_t = 1.55 kg
Volume of gas-transport system, prorated for one balloon	V_t = 2,100 cm^3
Volume of each packed balloon	V_P = 1,900 cm^3
Totals for a ten-balloon system (including factor F)	
TOTAL MASS:	63 kg
TOTAL VOLUME:	8.2×10^4 cm^3

VERTICALLY RISING PLATFORM: CASE 4

Payload mass: 1.0 kg; density altitude: 10^{-5} gm/cm^3	
Item	Value
Radius of unstretched balloon	$r_u = 79$ cm
Mass of fabric for each balloon	$m_b = 2.8$ kg
Mass carried by each balloon (excluding gas)	$m_L = 3.8$ kg
"Intrinsic balloon efficiency"	$\frac{m_p}{m_L} = 0.26$
"Total mass efficiency"	$m_p/m_T = 0.066$
"Volumetric efficiency"	$V_p/V_T = 0.052$
Mass of buoyant gas for each balloon	$m_g = 0.34$ kg
Mass of gas transport system (including gas generated), prorated for one balloon	$m_t = 3.8$ kg
Volume of gas-transport system, prorated for one balloon	$V_t = 5.1 \times 10^3$ cm^3
Volume of each packed balloon	$V_p = 3.5 \times 10^3$ cm^3
Totals for a ten-balloon system (including factor F)	
TOTAL MASS:	152 kg
TOTAL VOLUME:	19×10^4 cm^3

NOTES FOR THE VERTICALLY RISING PLATFORM

(a)	Typical values for extensible material, See Chapter VI, Table 3.
(b)	Appendix C.
(c)	From Chapter VI, Table 3.
(d)	From the assumed BeH_2 chemical gasogene; see Appendix B.
(e)	This is an assumed value. The results are not particularly sensitive to variations in this parameter.
(f)	An assumed value to allow for extras. Although difficult to estimate at this point, it is felt that extras will not more than double the total mass.
(g)	Chapter V, section on extensible balloons.
(h)	Discussed in Chapter II.
(i)	See Eq. (5.13).

The Superpressure Balloon as a Floating Platform

The flight duration of a Mylar superpressure balloon, carefully fabricated and properly designed to remain fully inflated during the entire diurnal temperature cycle, is limited only by the eventual deterioration of the fabric. Present uncertainty of the flux of ultraviolet radiation near the Martian surface does not permit an accurate prediction, but to say that such a balloon will remain aloft for many hours, and probably for many days, appears safe. It is, therefore, ideal as a platform to carry instruments to study the atmosphere and the planet's surface as the balloon drifts with the wind. The possibilities afforded by such experiments were discussed in Chapter II.

For numerical examples, consider two payloads; 1 kg and 10 kg. These figures include both the instrument package and such auxiliary equipment as the telemetry transmitter, the beacon gondola, and the control valves and circuits. The balloons are designed to float at an altitude in the Martian atmosphere where the atmospheric density is about 5×10^{-5} gm/cm^3 or roughly 7 to 25 km (see Chapter III). The properties of the balloon fabric will be taken from Chapter VI of this report; the analysis will follow the methods of Chapters II and V. On the basis of greatest efficiency, hydrogen is chosen as the buoyant gas. The chemical gasogene BeH_2, discussed in Appendix B, is hypothesized for this application.

HORIZONTALLY TRAVELING SENSOR

Parameters common to both cases		
Items	**Values**	**Notes**
Atmospheric density at first altitude of full inflation	$\rho_i = 5 \times 10^{-5}$ gm/cm^3	(a)
Thickness of fabric	$t_b = 0.0015$ cm	(b)
Density of fabric	$\rho_b = 1.4$	(b)
Packing ratio of fabric	$f_P = 0.8$	(c)
Balloon temperature parameter	$\chi = 0.85$	(d)
Payload density (assumed)	$m_p/V_p = 1.0$	
Buoyant-gas lifting efficiency	$\frac{m_L}{m} = 0.92$	(e)
Molecular-weight ratio	$\beta_0 = 14.5$	(e)
Gas-transport system's mass ratio	$m_g/m_t = 0.09$	(f)
Gas-transport system's volume ratio	$V_t/m_g = 15.0$	(f)
Factor to allow for "extra mass"	$F = 2.0$	(g)
Derived quantities		
C_V	4.7×10^{-5} gm/cm^3	(h)
C_A	2.1×10^{-3} gm/cm^2	(h)
μ	2.07×10^{-3} gm^{-1}	(i)

HORIZONTALLY TRAVELING SENSOR: CASE 1

Payload mass: 1.0 kg		
Items	**Values**	**Notes**
μm_p	2.07	
"Intrinsic balloon efficiency"	$m_p/m_L = 0.41$	(j)
"Total mass efficiency"	$m_p/m_T = 0.11$	(k)
"Volumetric efficiency"	$V_p/V_T = 0.09$	(k)
Mass of buoyant gas	$m_g = 210$ gm	(l)
Balloon radius	$r = 2.3$ m	(m)
Balloon mass (fabric only)	$m_b = 1.4$ kg	
Mass of gas-transport system (including gas generated)	$m_t = 2.3$ kg	
Volume of packed balloon	$V_p = 1300$ cm^3	
Volume of gas-transport system	$V_t = 3150$ cm^3	
Totals, including factor F		
TOTAL MASS:	9.4 kg	
TOTAL VOLUME:	1.1×10^4 cm^3	

HORIZONTALLY TRAVELING SENSOR: CASE 2

Payload mass: 10 kg	
Items	**Values**
μm_p	20.7
"Intrinsic balloon efficiency"	$\frac{m_p}{m_L} = 0.68$
"Total mass efficiency"	$m_p/m_T = 0.17$
"Total volumetric efficiency"	$V_p/V_T = 0.15$
Mass of buoyant gas	$m_g = 1.3$ kg
Balloon radius	$r = 4.2$ m
Balloon mass (fabric only)	$m_b = 4.7$ kg
Mass of gas-transport system (including gas generated)	$m_t = 14.5$ kg
Volume of packed balloon	$V_p = 0.42 \times 10^4$ cm^3
Volume of gas-transport system	$V_t = 1.9 \times 10^4$ cm^3
Totals including factor F	
TOTAL MASS:	58 kg
TOTAL VOLUME:	6.6×10^4 cm^3

NOTES FOR THE HORIZONTALLY TRAVELING SENSOR

(a)	See Chapter III.
(b)	Typical values for Mylar, see Table 3.
(c)	This is an assumed value. The results are not particularly sensitive to this parameter.
(d)	See Appendix A.
(e)	From Table 3.
(f)	For the assumed BeH_2 chemical gasogene, see Appendix B.
(g)	An assumed value to allow for extras.
(h)	See Eq. (2.13).
(i)	See Eq. (2.18).
(j)	Defined in Chapter II.
(k)	Discussed in Chapter II, see Eq. (2.2).
(l)	See Eq. (2.8).
(m)	See Eq. (2.17).

The Equal-Pressure Balloon as a Conveyance

As a means of transporting heavy loads on the planet, the equal-pressure buoyant-gas balloon especially is effective. We will assume that the balloon fabric is Mylar, so many of the parameters of the superpressure case carry over to this one. As a numerical example, we will consider a 100-kg payload. As before, the buoyant gas will be hydrogen carried as the compound BeH_2. Since the object is transportation in the lower atmosphere we assume a somewhat higher air density (7×10^{-5} gm/cm^3) than in the previous case. No provision will be made for ballast on the assumption that duration longer than one day will not be required.

Efficiencies for the total balloon system, m_p/m_T and V_p/V_T do not have the same real significance for a balloon used as a conveyance as they do for other balloon applications.* However, the payload mass and volume are arbitrarily included in the calculations for the equal-pressure balloon in order to preserve uniformity with the numerical examples previously given.

The notes cited in the superpressure balloon example apply here as well, except for the formula for C_V, which is Eq. (5.31).

---

*When the balloon's primary purpose is to move a package from a spot where that package has once served its function to another location, it may not make sense to include the mass and volume of the "freight" in the "total balloon-system mass." Whether the payload should or should not be included for a fair comparison of the system depends on the role of the balloon in the total space mission.

CONVEYANCE

Items	Values
Atmospheric density at altitude of first full inflation	$\rho_i = 7 \times 10^{-5}$ gm/cm^3
Thickness of fabric	$t_b = 0.0015$ cm
Density of fabric	$\rho_b = 1.4$
Packing ratio of fabric	$f_p = 0.8$
Buoyant-gas lifting efficiency	$m_L/m = 0.92$
Molecular weight ratio	$\beta_0 = 14.5$
Gas-transport mass ratio	$m_g/m_t = 0.09$
Gas-transport volume ratio	$V_t/m_g = 15$
Factor to allow for extra mass	$F = 2.0$
Derived quantities C_V	5.55×10^{-5} gm/cm^3 [see Eq. (5.31)]
Derived quantities C_A	2.1×10^{-3} gm/cm^2
Derived quantities μ	3.08×10^{-3} gm^{-1}
"Intrinsic balloon efficiency"	$m_p/m_L = 0.86$
"Total mass efficiency"	$m_p/m_T = 0.22$
"Volumetric efficiency"	$V_p/m_T = 0.23$
Mass of buoyant gas	$m_g = 10$ kg
Balloon radius (fully inflated)	$r = 8.1$ m
Balloon mass (fabric only)	$m_b = 16$ kg
Mass of gas-transport system (including gas)	$m_t = 110$ kg
Volume of gas-transport system	$V_t = 1.5 \times 10^5$ cm^3
Volume of packed balloon	$V_p = 1.4 \times 10^4$ cm^3
Totals (including payload and factor F)	
TOTAL MASS:	450 kg
TOTAL VOLUME:	4.3×10^5 cm^3

IX. CONCLUSIONS AND SUGGESTIONS

We started this study with a discussion of interesting experiments to be done on Mars that could be accomplished with the aid of balloons. We proceeded to derive a theory that permits us to examine quantitatively the capabilities of balloon techniques in any planetary atmosphere. In addition, we have investigated the problems of the interplanetary transportation of lifting gases and have examined various aspects of the operation of complete balloon systems on Mars. As a result of this study, we conclude that it appears feasible to use balloons as an aid to the exploration of Mars.

Specific Conclusions

(1) For a total usable payload (i.e., boosted to Mars), of less than 100 kg, it appears feasible (within the uncertainties that exist) to accomplish such missions as,

a. Launching 10 vertically rising extensible balloons with payloads of the order of 0.1 kg, to altitudes exceeding that at which the density is 10^{-5} gm/cm^3; or launching an equal number with payloads of the order of 1 kg to an altitude exceeding that at which the density is 5×10^{-5} gm/cm^3.

b. Placing a horizontally traveling superpressure balloon at an altitude exceeding that at which the density is 5×10^{-5} gm/cm^3, and carrying a payload exceeding 10 kg.

(2) If the total usable payload carried to Mars is increased to several thousand kilograms, lifting more or heavier payloads to higher altitudes than those suggested in (1) becomes possible, or alternatively, one might consider transporting by balloon (over the surface of Mars) loads of up to 1000 kg.

(3) Shipping hydrogen to Mars as a high-pressure gas has the advantage of being relatively simple, but presents technical problems if very high pressures are employed, and is relatively inefficient. Cryogenic transport becomes efficient only if the mass of the gas exceeds a few kilograms; a heat source is needed to gasify the liquid. Chemical gasogenes promise both efficiency and convenience, but require extensive research. The chemical method appears most favorable at the present writing, but research on all methods for gas transport is needed before a choice is made.

(4) It does not appear to be reasonable to consider the use of a hot-air balloon for which a burner or combustion heater supplies the heat for maintaining the flight. This is due to the relatively short durations available (of the order of tens of minutes) for large transported weights of combustible fuel and oxidizer. It it is possible to find a balloon fabric or design a "fabric greenhouse" so that the balloon strongly absorbs solar radiation, and emits infrared only weakly, it may be feasible to plan a sustained flight (i.e., during daylight hours) of a solar-radiation-heated hot-air balloon.

Suggested Research

Balloons appear to be promising candidates as vehicles to transport exploratory instruments on Mars. But a question remaining is: "In what areas is our knowledge critically deficient?"

There are two areas in which research is needed before such a system is designed: research on balloons themselves and research on Mars. Suggested lines of inquiry in these two areas are treated separately below. Nearly every phase of the suggested balloon research has value for terrestrial applications as well as contributing to the effectiveness of a Mars expedition.

BALLOONS

Balloon fabrics. For nonextensible buoyant-gas balloons, research is needed on a fabric whose manufacture leaves no pinholes, and which can then be reliably formed into a balloon envelope that is free from strains. The fabric must be able to withstand solar ultraviolet radiation at somewhat higher levels than contemporary balloon fabrics and may have to resist trace amounts of ozone. It should have a very high tensile strength and resistance to abrasion. It should not become brittle at very low temperatures. Furthermore, it must not lose these qualities during the long periods of storage in space. For temperature stability in the superpressure balloon, the fabric should absorb neither sunlight nor far infrared strongly. The fabric must be capable of being sterilized.

Mylar fills the requirements (except possibly for sterilizability) as nearly as any material today. However, it is possible that further research in Mylar laminates or in new "exotic" films will turn up something better.

When a fabric that appears suitable has been found, laboratory research will be required in order to determine the temperature characteristics of the film under simulated space storage and Mars' atmospheric conditions. It will also be necessary to subject the fabric to appropriate environmental tests. It may be that new fabrication and testing techniques will have to be developed to meet the very stringent reliability requirements imposed on any remotely operated experimental device.

For extensible balloons, new fabrics should be sought that are insensitive to ultraviolet radiation and ozone and that do not become brittle at the cold temperatures expected in Mars' atmosphere. Other desirable features would be the ability to stretch by a larger factor, and to a smaller thickness, than rubber or neoprene before bursting. Environmental testing requirements would be much the same as for nonextensible balloons.

Gas-transport methods. To achieve an efficient balloon system, considerable research will be required early in the program in the form of a thorough study of the whole problem of hydrogen transport to another planet. The numerical examples in the present report are based on hydrogen generation by thermal decomposition of beryllium hydride, but as emphasized in Appendix B, it is by no means certain that this method can actually be developed into a workable gas-generation system. A number of other promising reactions are suggested in Appendix B. Successful use of a hydrogen-generating chemical reaction requires compounds (1) that contain a large mass fraction of hydrogen, (2) that are stable for long periods, and (3) that can be made to release hydrogen in a way that is both convenient and energy-stingy. Such a method will only be developed through a thorough experimental program. And, of course, once a satisfactory reaction is found, lightweight miniaturized equipment such as reaction vessels and valves must be developed and combined into a system that is capable of reliably delivering hydrogen at the rate required.

Transport of hydrogen under high pressure might, on closer examination, prove to be a more favorable solution than it appeared to be in the present study. It has the advantage of simplicity and the capacity for rapid gas generation.

Cryogenic storage of liquid hydrogen is treated only briefly in this report. The mass estimates presented in Appendix B would be more optimistic if a more effective insulating material or insulation method were found, or if a reliable closed-cycle liquifying system of low weight were developed. In the total program of research for Mars balloons, gas transport deserves special emphasis.

Launching techniques. Remote launching requires light, compact, and reliable equipment. An engineering study of this problem — particularly the problem of launching from the ground — would be of great interest.

MARS' ATMOSPHERE

The greater the amount of reliable data on the Martian atmosphere, the better a given balloon system can be "tailored" to its mission in that atmosphere. Today, reliable data are all but nonexistent. Composition, temperature, and pressure are known only within very broad limits.

It may be impossible to form a satisfactory estimate of pressure and temperature before a probe actually enters the atmosphere (although indirect methods may be found any day that give more precise answers than the guesses of today). However, should observations of Mars be undertaken from a satellite outside Earth's atmosphere, the composition and chemistry of Mars' atmosphere would be much better understood; in particular, it should be easy to determine the ozone content by absorption spectroscopy, and this would lead to a better estimate of the ultraviolet flux.

Every datum that is accumulated before the time of a major landing expedition will be of use to the balloon designer; he should therefore, have every facility for keeping abreast of the information as it becomes available.

Appendix A

BALLOON TEMPERATURE

The temperature of the gas in a balloon is, as stated earlier, one of the most important of the parameters that govern the balloon's performance, but it is also one of the most difficult to estimate. The hot-air balloon depends for lift solely on the temperature difference across the fabric; the lift of buoyant-gas balloons, while not dependent solely on the temperature difference between the gas inside and the air outside, is much affected by this parameter. Several physical processes can transfer heat to or from the balloon; in general neither the gas nor the fabric envelope will be isothermal. The quantity we seek to estimate, which we call the "balloon temperature," is defined as the temperature that an isothermal bubble of gas would have if it occupied the same volume as the balloon gas at the same pressure. (This is the quantity symbolized by T' in the equations of this report.) In this appendix we discuss the processes of heat flow that ultimately determine the balloon temperature, and we estimate this parameter under a variety of conditions.

Direct Heat Transfer to Balloon Gas

One process by which the gas within the balloon can directly gain or lose heat is direct absorption of sunlight or infrared radiation or emission of infrared radiation. Both ammonia and methane have infrared absorption bands, so direct coupling between the balloon gas and the radiative environment must be considered if either of these gases should happen to be used. Neither hydrogen nor helium absorbs infrared radiation and neither absorbs solar radiation except in the vacuum ultraviolet part of the spectrum.

The most important process for the transfer of heat into the balloon gas is free convection. Unless a heater is used (as in the hot-air balloon) convective transfer occurs only to and from the balloon envelope. If the fabric temperature remained constant, the gas within the balloon would eventually reach a temperature distribution in convective equilibrium with the balloon envelope, corresponding to a particular "balloon temperature" as discussed above.

For temperature differences of a few degrees, the rate of heat transfer can be considered to be directly proportional to the temperature difference. Even for differences of the order of 100 degrees centigrade, the error incurred by making this approximation is probably small compared to other uncertainties in the analysis. Assuming a nitrogen atmosphere with temperatures and densities in the range specified in Chapter III, the rate of heat transfer by free convection to the outside air is approximately,(A.1)

$$\frac{dQ_c}{dt} \approx 10^{-5} A(\Delta T) \text{ cal/sec} . \qquad (A.1)$$

Terrestrial experience shows that a balloon responds rapidly -- within a few minutes -- to such changes in thermal environment as sunset.

Another "direct" process that brings about temperature changes in the balloon gas arises from the work the gas does against atmospheric pressure during the balloon's ascent (or, the work the atmosphere does on the gas of an equal-pressure balloon if it should descend). If the process were adiabatic (it can be easily shown), the temperature of the balloon gas would decrease with increasing altitude:

$$- \frac{\partial T}{\partial z} = \Gamma_g = \frac{g}{c_p} \left(\frac{M_a}{M_g} \right) \text{ deg/cm} ,$$

where g is the local acceleration of gravity, and c_p is the specific heat of the balloon gas at constant pressure.* The successive

*The ratio of the cooling rate Γ_g to the atmospheric adiabatic lapse rate Γ_a is $\frac{\Gamma_g}{\Gamma_a} = \frac{(c_p)_{air}}{(c_p)_{gas}} \frac{M_a}{M_g} \approx 1.1$ for a hydrogen-filled balloon in a nitrogen atmosphere. So the adiabatic cooling rate for hydrogen in a balloon is slightly greater than Γ_a.

temperatures during the balloon's rise are coupled to its rate of rise, so balloon temperatures actually should enter into the equations of motion. The effect of expansion cooling is to slow the rate of rise, hence the term "thermal drag" used by some writers. However, for most applications, there is no need to study in detail the temperature of the rising balloon. If it cools to such a degree that buoyancy is lost, its rate of rise will slow to zero. Then, as it approaches temperature equilibrium with the atmosphere and the radiation environment, it will (if properly designed) resume its rise to its ultimate floating altitude.

Generally, we will assume that the balloon temperature is at its equilibrium value. The calculation of the time constant for the system suggests that such an equilibrium is rapidly established, and this is borne out by experience. Since the equilibrium balloon temperature is ultimately determined by exchange of heat with the fabric, we now discuss the factors that contribute to heat loss and gain by the fabric.

Heat Transfer to the Balloon Fabric

As has been discussed, heat is transferred from the fabric to the gas inside the balloon by convection. The gas within the balloon, therefore, acts as a heat sink. The fabric also exchanges heat with the surrounding air by convection; "free" if the balloon is stationary with respect to the surrounding air, "forced" if it is rising. Convection tends to tie the fabric temperature to the temperature of the surrounding air. But the fabric temperature is also strongly influenced by the radiation environment. During the day, the fabric absorbs sunlight and both day and night it absorbs infrared radiation from the ground. At all times it emits infrared in accordance with its temperature and its emissivity in the far infrared. The absorption of sunlight depends upon the reflectivity and the absorption coefficient of the balloon fabric for the solar spectrum; if the fabric is transparent through part of the solar spectrum (e.g., Mylar), the process is particularly complicated. The absorption and emission of the far-infrared radiation similarly depends upon the infrared reflectivity and the absorptive--emissive power of the fabric. (For the ground and balloon temperatures of importance in this study, 200°-400°K, by "infrared" we are referring to wavelengths longer than 6 microns.)

The fabric will not be isothermal. The heat input of both solar and ground radiation varies for different parts of the balloon, and the thermal conductivity is sufficiently small that along the surface of the fabric heat will be transported slowly. (In contrast, heat transport through the film is adequate to prevent the existence of any significant temperature gradient across the film.) We will, nevertheless, refer to a "mean" temperature for the balloon fabric, T_b, in order to make it possible to compute estimates. The "effective balloon temperature" (T') defined in the first paragraph of this appendix will be assumed to be equal to this mean T_b. This assumption is made here because the gas inside the balloon will come to equilibrium with the balloon fabric, which does not, itself, have a significant heat storage capacity. A more refined treatment would consider the possible differences between the effective balloon temperature, T', and the mean fabric temperature T_b, but except for the hot-air balloon, it is reasonable to consider them approximately equal so long as we are dealing with convective processes. For radiative losses from the film, since they depend upon the fourth power of the temperature, the proper average over the temperature distribution would be somewhat different, and it would be somewhat better to take

$$T_r^4 = \eta_r T_b^4 \quad ,$$

where T_r is the fabric temperature to be used in computing radiative losses, and as before, T_b is the fabric temperature (assumed to be equal to T') used for convective losses to the outside air; the equation defines the factor η_r.

The heat inputs to the fabric, omitting coupling to the gas inside are (1) sunlight, (2) convection of heat from outside air, (3) radiation from the ground. The amount of sunlight absorbed will depend on the integrated reflectivity and absorptive power of the film and on its thickness. We will combine all of these into one parameter, α_b, the "effective absorptive power" of the fabric for sunlight. The convection term has already been discussed. It is unnecessary to deal explicitly with forced convection since we are concerned here with equilibrium. Moreover, rough calculation indicates that the magnitude of heat transfer (during the rise of the balloon) by forced convection is roughly the same as that which would be computed if free convection were assumed, for the rates of rise considered in this report.

The ground-radiation term can be estimated only roughly since its magnitude will depend not only on the ground temperature but also on the emissivity of the ground. We assume effective ground radiation temperatures (T_G) of 200°K at night, and 300°K by day (see Chapter III.) If a cloud should pass between the balloon and the ground during the day, we assume that the effect can be approximated by taking the ground-night case.

In equilibrium we assume that the following equation can be written to express the various heat fluxes to the balloon fabric:

$$\alpha_b S \frac{A_B}{4} + \epsilon_b \sigma_B T_G^4 \frac{A_B}{2} - \epsilon_b \sigma_B T_b^4 A_B - \frac{dQc}{dt} = 0 \quad .$$

In this equation σ_B is the Stephan--Boltzmann constant, S is the solar constant for Mars, T_G is the effective radiative temperature for the Mars surface under the balloon, T_b is the effective temperature of the balloon fabric, α_b is the absorptive power of the fabric for sunlight (all wavelengths), and ϵ_b is the emissive power of the fabric for far-infrared radiation. The term dQc/dt represents the convective heat transfer with the surrounding atmosphere. Besides the uncertainties mentioned in Chapter III, we must recognize that the temperature distribution within Mars' atmosphere is poorly known at the present time. For the calculations of this section, an air temperature of 180°K was assumed for day and night, but this should be considered only as a representative value.

In order to exhibit the manner in which the radiative properties of the fabric influence the balloon's equilibrium temperature, computed in accordance with the above equation, the diurnal temperature range of the balloon was computed -- the difference between the maximum temperature during the day and the minimum temperature at night. For the daytime maximum, the solar radiation term was included, and T_G was assumed to be 300°K; for the nighttime minimum, the solar term was omitted, and T_G was assumed to be 200°K. The emissive power of the ground was assumed to be 0.9. The solar constant used was 0.013 cal $cm^{-2}sec^{-1}$. All these values were chosen purposely to obtain a high estimate of $(\Delta T)_{max}$. Figure 9 shows the results, lines of constant $(\Delta T)_{max}$, with the fabric's infrared emissivity as ordinate, solar-spectrum absorptivity as abscissa. No claim is made that the results presented in this figure are accurate. However, they may be useful in suggesting how the radiative properties of the fabric influence the temperature range. A plot of the temperature maxima would appear similar to these curves since the minimum nighttime balloon temperature calculated (158°K) was only 22 degrees colder than the assumed air temperature, 180°K.

Figure 10 shows a plot of the minimum temperature as a function of ε_b. The ratio of the minimum temperature inside the balloon at night to the ambient air temperature, χ, exceeds 0.87. We adopt the value 0.85 for the calculations presented in Chapter V in the section on superpressure balloons.

The question of balloon equilibrium temperature is an important one, and there are many uncertainties in attempting to estimate it for any particular balloon material. It is, therefore, mandatory that before a Mars balloon is finally designed, experiments be conducted in the laboratory to determine this parameter under the range of conditions that are anticipated for Mars. Estimates are given in this report to serve as a planning guide, but they in no sense substitute for laboratory experiments.

Mylar is the balloon material chosen for most of the examples in this report. Examination of the radiative properties for this

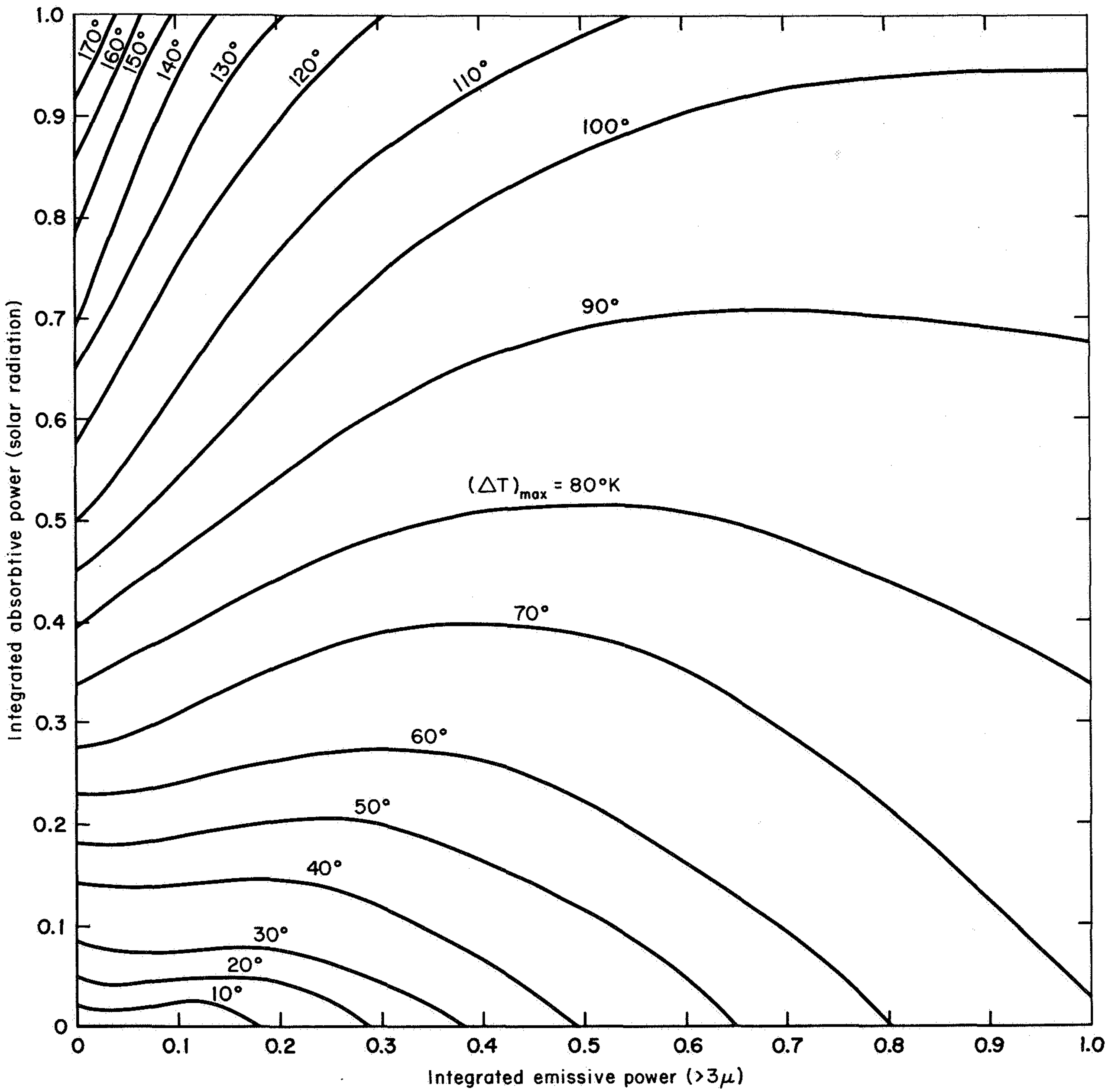

Fig. 9 — Maximum day-to-night temperature variation of balloon
[$(\Delta T)_{max} = T'_{max} - T'_{min}$, under specified assumptions]

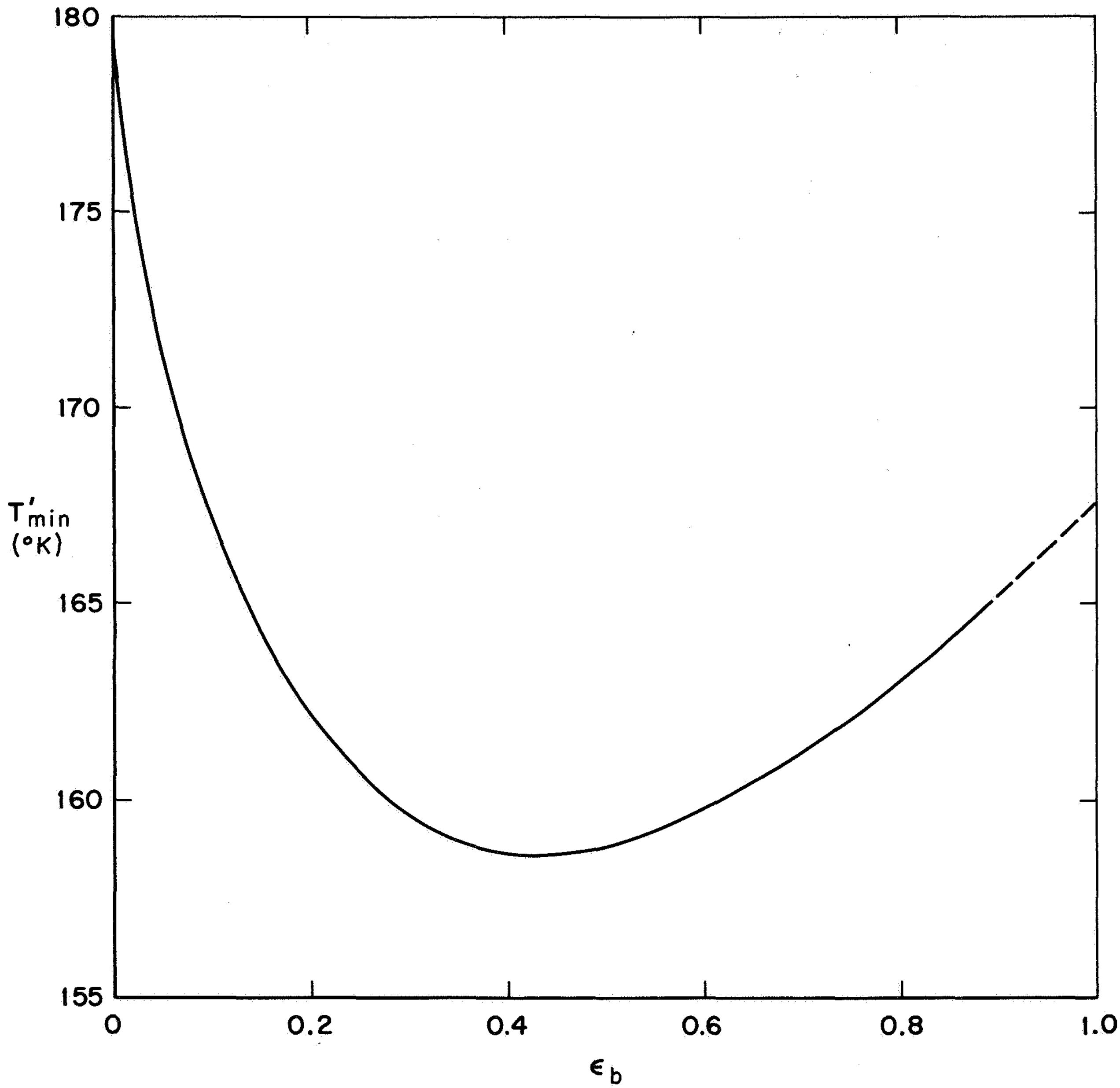

Fig. 10 — Minimum balloon temperature at night versus integrated emissive power, under specified set of assumptions ($\lambda > 3\mu$)

material as reported in Ref. A.2 suggests values of $\alpha_b = 0.015$, $\epsilon_b = 0.30$ for this material. These are estimates only, because (1) the available data on emissive power do not include wavelengths longer than 15 microns, and (2) the reflectivity of the material for sunlight and infrared has not been adequately taken into account. As stated in the above paragraph, reliable estimates of balloon temperatures must await further laboratory data. However, for planning purposes, using the analysis just presented, we can estimate that for an air temperature of 180°K, a Mylar balloon will reach a temperature of about 181°K during the day, and a temperature of about 159°K at night, a temperature variation of 22°. Since the absorptive power for solar radiation is low, while that for far-infrared radiation is comparatively high, the primary cause of the diurnal temperature variation for this material is the diurnal change in ground temperature. If a dust cloud should pass under the balloon during the day, its temperature would drop significantly.

A balloon of black material, on the other hand, is influenced both by sunlight and by radiation from the ground. Highest sunlit temperatures are achieved with a balloon having a high absorptive power for solar radiation in combination with a low emissive power in the far infrared. Figure 9 illustrates this point. A practical application of this principle is discussed in the section of Chapter V that deals with the hot-air balloon.

<u>REFERENCES FOR APPENDIX A</u>

A.1 Jakob, M., <u>Heat Transfer</u>, Vol. 1, Wiley and Sons, New York, 1949.

A.2 General Mills, Inc., Mechanical Division, <u>Balloon Barrier Materials</u>, Final Report, AFCRC-TR-58-211 (DDC No. AD-152504), 1958.

Appendix B

ANALYSIS OF GAS-TRANSPORT METHODS

In this appendix the various methods for gas transport are analyzed in some detail. As elsewhere in this report, the calculations should be regarded as illustrative rather than definitive, although considerable care has been used in choosing values for parameters in order to make the results as meaningful as possible.

PRESSURIZED GASES

Mass Ratio

For a thin-walled, spherical pressure vessel, the stress σ (atm) is given approximately in terms of the radius, r, the internal pressure, p, and the wall thickness, t, so long as $p \ll \sigma$ by the relation[(B.1)]

$$\sigma = \frac{pr}{2t} \quad . \tag{B.1}$$

For a particular material, there will be a maximum allowable stress, σ_m. If a pressure vessel is designed to function at this maximum allowable stress, the ratio of the mass of the container plus gas to the mass of available gas,

$$\frac{m_t}{m_g} = \left[\frac{3\rho_t \eta_g}{2\sigma_m \rho_g} + 1 \right] \frac{f_h}{1 - f_g} , \tag{B.2}$$

where η_g is the "pv" value of the gas (pv = 1.0 at 0°C, 1 atm), f_h is a factor to allow for hardware, plumbing, etc., ρ_t is the density of the vessel's material, ρ_g is the gas density at 0°C, 1 atm, and f_g is the fraction of the initial charge of gas that leaks out during the spaceflight; f_g is added to m_t in Eq. (B.2) because it represents mass that must be carried but is other than available gas. The "mass efficiency" of the transport system is the reciprocal of the mass ratio just computed.

To keep the volume of the vessel to a minimum, the highest pressures possible should be employed. A design pressure of 1000 atm was used to make comparisons in this section.

Hydrogen. Ordinary steel is permeable to hydrogen; to prevent diffusion of the gas into the metal, one must combine a special steel alloy with an impermeable inner coating. Such a vessel, if it were required to contain hydrogen for a number of months at very high pressures (e.g., several thousand atmospheres) would require very careful design and testing.[B.2] Even so, there would be some leakage during a months-long spaceflight; somewhat arbitrarily, the "leakage factor," f_g, will be assumed to be 0.5. The "hardware factor," f_h, will be given the value 1.2.

Helium. Though helium diffuses less readily into ferrous alloys, the same leakage factor will be used as for hydrogen. Since f_g is clearly a function of the flight's duration, its value of 0.5 is purely illustrative.

Methane. The critical temperature of methane is 192°K; the gas cannot be liquified by pressure at temperatures higher than this. Its leakage factor, we will assume, can be held to 0.2.

Volume Ratio

Since the wall thickness is a small fraction of the radius of the vessel, as long as p is much smaller than σ_m, the volume is approximately equal to the volume of the gas under pressure. Therefore,

$$V_t/m_g = \frac{\eta_g f_h}{p \rho_g (1 - f_g)} \tag{B.3}$$

for p in atm.

Estimated Efficiencies for Gases at a Pressure of 10^3 atm

Gas	ρ_g gm/ℓ	η_g	Material	σ_m (atm)	ρ_t (gm/cm^3)	f_g	f_h	efficiency m_g/m_t	V_t/m_g (cm^3/gm)
H_2	0.089	2.46	coated steel	1.5×10^4	7.7	0.5	1.2	0.02	66
He	0.178	2.42	steel	1.5×10^4	7.7	0.5	1.2	0.04	36
CH_4	0.717	2.78	steel	1.5×10^4	7.7	0.2	1.2	0.16	5.7

Notes: Values for η_g are for a gas temperature of 100°C for conservative design.

Values for σ_m represent conservative engineering practice.

Values were derived using Van der Waal's constants from the Handbook of Chemistry and Physics (30th ed., 1947).

Valving the Gas

The problem presented by valving hydrogen or helium at very high pressure may not be as acute as might be anticipated. One might expect that the extreme expansion ratio (perhaps 10,000-to-1) would result in extreme cooling, and even in liquification of the gas. However, both hydrogen and helium will probably be well above their Joule-Thomson maximum inversion temperature (195°K for H_2, 23.6°K for He). If they are allowed to transpire through a porous plug, therefore, their temperatures will actually increase. Friction will also act to warm the gas. Even without details of the actual engineering design, one can easily imagine a one-shot valve that would allow the high-pressure gas to transpire out of the pressure tank through a porous plug. A diaphragm valve, since it would be activated only once -- when the balloon was to be filled -- should not present too difficult a design problem.

General Remarks

One conspicuous advantage of gas transport under high pressure is that the gas is then available without further complications;

it can be provided at any predetermined rate. Possibly, the problems in carrying hydrogen at extreme pressures are not as severe as anticipated. Coating techniques and special alloys could alleviate the leakage problem, and specially designed vessels might be lighter and more efficient. (Since helium grants no conspicuous advantage, developmental research probably should concentrate on hydrogen transport.) Possibly, too, the simplicity and probable reliability of a high-pressure system would out-weigh its disadvantages of one-shot operation and relatively low mass and volume efficiencies.

LIQUIFIED GASES

A liquified gas must be carried in a vessel that can withstand the vapor pressure of the gas in equilibrium with the liquid. This pressure, p, depends strongly upon the temperature (approximately as an exponential function of 1/T). If low temperatures are required, the vessel must also be provided with insulation. Analysis of the vessel itself can proceed along the same lines as were followed for pressure vessels in the last section above. The mass of gas available on Mars, m_g, is related to the volume of the tank, V_t', and the density of the liquid, ρ_ℓ by

$$m_g = V_t' \, (1 - f_g)\rho_\ell f_F \quad ,$$

where f_g is the fraction of gas lost during the trip, f_F the fraction of the tank originally filled. It should be noted that V_t' is the capacity of the tank only; the volume of the transport system, V_t, will be equal to V_t' plus, if low temperatures are required, the volume of insulation. Assuming spherical geometry,

$$\frac{V_t}{m_g} = \frac{x^3 y f_h}{\rho_\ell f_F} \quad , \qquad \text{(B.4)}$$

where $y = 1/(1 - f_g)$, the ratio of the original mass of liquid to that surviving after the spaceflight, $x = r_2/r_1$, the ratio of the outer radius of insulation to its inner radius.

Since m_t is the sum of the masses of the insulation, the pressure tank and the available gas,

$$\frac{m_t}{m_g} = \left\{ y \left[\frac{\rho_{in}(x^3-1)}{f_F \rho_\ell} + \frac{3p\ \rho_t}{2\sigma_m \rho_\ell f_F} + 1 \right] + \frac{m_Q}{m_g} \right\} f_h \qquad \text{(B.5)}$$

or

$$= y \left[\frac{\rho_{in}(x^3-1)}{f_F \rho_\ell} + \frac{3\rho_t t_{min}}{\rho_\ell\ r_1} + 1 \right] f_h \ ,$$

whichever is greater. In the second expression, t_{min} is the minimum allowable thickness of the pressure-vessel wall; r_1 is the radius of the pressure vessel (corresponding to the inner radius of the insulation); m_Q is the mass of the heat source required to gasify the liquid, ρ_{in} is the density of the insulation, and f_h is a "hardware factor" as before.

The above expressions for m_t/m_g, V_t/m_g, in terms of x and y do not completely solve the problem, since these quantities are as yet unspecified. To complete the analysis, we must consider the various gases individually. For ammonia, the steps of this computation can be performed immediately. For hydrogen and methane, the computations require further analysis of the cryogenic problem. Results appear in Table 5.

<u>Hydrogen.</u> Hydrogen can be stored as a liquid only if it is below its critical temperature, 33°K; at 1 atmosphere vapor pressure, its temperature is 21°K. These temperatures are so low that detailed attention must be paid to the design of the cryogenic system. An insulated, vented cryogenic storage system for liquid hydrogen will be analyzed later in this section.

<u>Methane.</u> The critical temperature for methane is relatively high, 191°K; at 112°K its vapor pressure is 1 atm. These temperatures are sufficiently high that we can consider either cryogenic storage inside the spacecraft, or "no-loss" storage using radiation into space to balance the heat flux into the cryogenic container from the spacecraft.

Ammonia. The critical temperature for ammonia is +132°C, so low temperatures are unnecessary for storage of liquid ammonia. In order to achieve a conservative design, we will consider a steel pressure vessel that can withstand the vapor pressure of ammonia at 100°C, 14.4 atm. For ammonia, since no insulation is required, $x = 1.0$; and since we expect no extraordinary losses, we will assume by convention that $y = 1.2$ to allow for ordinary leakage.

The following paragraphs discuss three possible methods for storage in space of cryogenic liquids (specifically liquid hydrogen).

No-loss storage. Since the spacecraft will presumably be at a temperature near 300°K, and no method of thermal insulation, either by insulating materials or by radiation shields, is perfect, the only way a cryogenic vessel can be kept cold during the long space flight without either evaporating some of the liquid or employing an active refrigeration system, is by allowing it to radiate heat to something colder than itself. If the spacecraft is attitude-controlled, one can mount the cryogenic vessel externally on the shady side of the spacecraft and radiate heat to space. The effective radiation temperature of the celestial sphere will be assumed to be 0°K for purposes of calculation. The effective radiation temperature varies with the celestial latitude and longitude, but unless radiation from a nearby planetary body is included, the effective sky temperature probably does not exceed about 8°K.[B.3] The vessel must, of course, be protected from radiation on Earth during the first few days of the flight and from Mars during the last days. We will assume that this problem has been solved, and also that there is no important heat transfer to the spacecraft via tubes, brackets, or the like.

We will consider a vessel mounted on the shady side of, but insulated from, the spacecraft. The sort of insulating material that would be best in this application is, in effect, a "baklava" of radiation shields separated by lightweight powder.[B.4]

We will now estimate the thickness of insulation required to maintain the liquid at a given temperature. Assume that A_1 is the area of the cryogenic vessel in contact with the insulation, and that

A_2 is the area that radiates to space. It is of primary importance that the geometry be such that the area A_2 on the vessel receives no radiation from the spacecraft.

Assume that the temperature drop across the insulator is about 300°K, that the heat conductivity of the insulating material is 10^{-7} cal/sec-cm-deg (a representative value for modern multilayer insulating materials) and that the radiating surface of the cryogenic vessel has emissivity 0.9. By equating the fluxes of heat conducted into the vessel from the spacecraft, and heat radiated from the vessel to space (here assumed to be at 0°K), we can solve for the insulation thickness,

$$t_i \approx 2.5 \times 10^7 \left(\frac{A_1}{A_2}\right) T_1^{-4} \text{ cm} \quad . \tag{B.6}$$

It would be difficult to design a small system so that A_1/A_2 is less than or even equal to 1, since the radiating surface of the pressure vessel must be shielded from thermal radiation and solar reflections from the spacecraft. The resulting values for insulation thicknesses are in the table.

Required Thickness, t, of Insulation (cm)

Temperature of gas, T (°K)	For conduction—radiation ratios of $A_1/A_2 = 5.0$	$A_1/A_2 = 1.0$	$A_1/A_2 = 0.1$
20	780	155	15.5
40	50	10	1.0
80	3	0.6	<0.1

This analysis is only approximate, but it suggests that while in a small cryogenic vessel temperatures near 80°K are probably achievable by radiation balance alone, temperatures near 20°K are not. We can, therefore, store methane by radiation balance, but not hydrogen, unless a way is found to reduce A_1/A_2 to the order of 0.1.

There are several serious disadvantages to the system just discussed. One is the necessity of transferring the liquid from the cryogenic vessel mounted outside the spacecraft to an insulated vessel inside the entry capsule prior to entry into the Martian atmosphere. Such a transfer will entail unavoidable losses of cryogenic liquid besides adding complexity to the operation. Another disadvantage is the dependence on the attitude-control system of the spacecraft. It would be disastrous for that system to fail and for sunlight to fall directly on the radiating surface. A more practical cryogenic storage system that can be used for either hydrogen or methane is discussed in the next section.

Vented static storage inside spacecraft. The heat of vaporization of liquid hydrogen is low, 108 cal/gm, but we can, in principle, absorb the unavoidable heat flux into a container carried inside the spacecraft by vaporizing the liquid. This results in a loss of liquid mass. We assume that the hydrogen is vented to the outside, keeping a constant pressure of about 1 atm inside the cryogenic vessel. For a particular choice of parameters -- total flight time, mass of hydrogen needed on Mars, acceptable container size, and type of insulation material -- there will be an optimum design, since we can trade between carrying extra insulation and carrying extra liquid hydrogen to vaporize.

The performance of such a system may be analyzed as follows: The rate of mass loss by evaporation, assuming negligible heat conduction (through pipes, fittings, etc.) can be approximated for a spherical vessel by the expression:

$$\dot{m}_g = B\left(\frac{x}{x-1}\right) = B\left(\frac{t_i + r_1}{t_i}\right) , \tag{B.7}$$

where $x = r_2/r_1$, the ratio of outer and inner radii of the insulating material, and t_i is the thickness of the insulating material,

$$B = \frac{4\pi k r_1 (\Delta T)_\ell}{H} \quad ;$$

$(\Delta T)_\ell$ is the temperature difference between the cryogenic liquid and the spacecraft, and H is the heat of vaporization.

Assuming a constant rate of mass loss during the flight, the following expression can be derived, relating x, y, the surviving gas m_g, and the time of flight τ:

$$x = \frac{y - 1}{y - \alpha_\ell \tau \left(\frac{y}{m_g^2}\right)^{1/3} - 1} , \tag{B.8}$$

where

$$\alpha_\ell = \left(\frac{3}{4\pi\rho_\ell f_F}\right)^{1/3} \frac{4\pi k(\Delta T)}{H} .$$

Using y as the independent variable, we can solve Eqs. (B.5) and (B.8) simultaneously to find the values of x, y that make (m_t/m_g) a minimum. For purposes of comparison, we will use these optimum values.

Table 5 shows the results for hydrogen and methane (and ammonia), carried as liquids. For it, "optimum" values for m_g/m_t and V_t/m_g were computed as discussed, assuming static vented storage in an insulated spherical cryogenic vessel for 2×10^7 sec (about 8 months). The thermal conductivity of the insulating material, k, was assumed to be 1×10^{-7} cal cm^{-2}sec^{-1}deg^{-1},(B.4) f_h to be equal to 1.2, and the other physical constants were typical handbook values. Allowance was made for the additional mass and volume of a heat source to gasify the liquid and heat the gas to 0°C. A later section in this appendix discusses heat sources.

Note that the efficiency of this method, as measured by the ratio m_g/m_t, increases markedly as large amounts of gas are carried.

Table 5

ESTIMATED EFFICIENCIES FOR LIQUIFIED GASES
(8-MONTH STATIC STORAGE)

m_g (kg)	m_g/m_t	V_t/m_g (cm^3/gm)
	HYDROGEN	
0.1	0.003	3500
1.0	0.03	430
10.0	0.13	100
100.0	0.25	43
	METHANE	
0.1	0.08	71
1.0	0.27	17
10.0	0.43	8
100.0	0.52	5.8
	AMMONIA	
Any	0.47	3.4

RELIQUIFACTION OF HYDROGEN VAPOR

At temperatures below its maximum inversion temperature, 195°K, hydrogen can be cooled by transpiration through a porous plug. Joule-Thomson cooling is convenient and simple, and there also is always the possibility of cooling the gas by causing it to do work, as in an expansion turbine. In principle, either or both of these methods could reliquify in a closed cycle the hydrogen that boils off during a flight to Mars. The volumetric requirements of such a system are modest.

Beyond the heat rejection needed to liquify the gas, we must also allow for the conversion of ortho- to para-hydrogen. This conversion is troublesome because it normally occurs very slowly and generates heat. The usual practice is to accelerate the establishment of the equilibrium ortho/para ratio by means of a catalyst and reject the heat that results from the conversion before the liquid is pumped back into the cryogenic container.[(B.5)]

The design of a small, relatively lightweight, closed-cycle hydrogen liquifier should be well within the ability of today's cryogenic engineers. Unfortunately, its inherently greater complexity than that of a static system and its reliance on outside power would decrease the reliability of any transporter of liquified gas to Mars. Moreover, for amounts of gas under about 5—10 kg (the point where static cryogenic storage becomes fairly efficient), it would probably present no significant advantage in weight and volume over the best of the chemical systems.

HEAT REQUIREMENTS AND GENERATION METHODS

Before any of the liquified gases can be used to provide balloon gas, heat must be supplied both to vaporize the liquid and to bring the gas up to the operating range of the balloon material. The total quantity of heat required, Q, can be written

$$Q = m_g \left[H + (T_0 - T_\ell)c_p\right] + W \quad ,$$

where H is the heat of vaporization; T_0, T_ℓ are the operating temperature and the temperature of the liquid, c_p is the specific heat of the gas at constant pressure, and W is the work expended in filling the balloon, expressed in units of heat.

A number of possible heat sources is briefly discussed below.

Gas and surroundings. One source of heat, after the planet is reached, is the surrounding atmosphere; another is the heat capacity of the spacecraft structure if thermal contact is made between the pressure vessel and large metal parts of the spacecraft. By cooling as it boils, ammonia could itself supply some heat. The effectiveness of such heat sources cannot be estimated precisely, but it appears unlikely that they could make other heat sources superfluous.

Solar radiation. The solar constant at Mars is about 0.01 cal $cm^{-2}sec^{-1}$ (see Chapter III). With an efficiency of about 10 per cent, a collection area of 1 m^2 would provide heat at the approximate rate of 1 kcal/min.

Reactor. If a nuclear reactor is carried to provide power for other purposes, power may be no problem. It will be necessary only to be aware of the requirements and to make provision for supplying heat when required.

Batteries. Batteries could supply the energy needed, but only at the expense of energy that could be used to power other experiments. Furthermore, chemicals would seem a more direct means of generating heat than would the intermediate step of an electric current.

Chemical heat generation. Here we must consider (1) the mass efficiency or the heat generated per gram of reactants, (2) the reaction rate, and (3) the degree of control that can be exercised upon the reaction. For high mass efficiency, the most interesting reactions are those with compounds of the lightest elements.

(a) Hydrogen combustion: If the balloon gas to be generated is hydrogen, a way of supplying heat would be to carry 0_2 under pressure and use the familiar reaction[(B.6)]

$$2H_2 + 0_2 = 2H_20 + 136 \text{ kcal} \quad .$$

At low temperatures the reaction requires a catalyst such as colloidal platinum.

In order to include the mass and volume of oxygen used in this reaction, we now estimate the ratios m_t/m_g, m_g/V_t for oxygen using Eqs. (B.2) and (B.3). Assuming a steel vessel and 200 atm pressure, 20 per cent leakage, and a "hardware factor" of 1.2, m_t/m_g is approximately 1.4, m_g/V_t is approximately 0.17 gm/cm^3. The combustion of hydrogen produces 1 kcal with the consumption of about 0.03 gm H_2, and 0.24 gm 0_2 or 3.8 kcal per gram of reactants.

(b) Other combustion reactions: If methane is carried as the buoyant gas, its combustion could be used as a heat source in a similar fashion. Generation of 1 kcal by combustion of CH_4 (assuming complete combustion) requires about 0.3 gm O_2, and about 0.075 gm CH_4 or 2.7 kcal per gram of reactants; it produces approximately 0.2 gm CO_2, and 0.17 gm water vapor.

The combustion of many other compounds follows along similar lines. For example, complete combustion of about 0.15 gm ethyl alcohol, with 0.3 gm O_2 also produces about 1 kcal or about 2.2 kcal per gram of reactants.

(c) Thermite reaction: The thermite reaction of iron oxide and aluminum has the advantage that gas is neither generated nor consumed. It generates approximately 1 kcal per gram of reactants,[B.7] but if the very high temperatures are to be used, additional mass in the form of a suitable reaction vessel and heat exchanger would be required.

"Adopted" Heat Source

For purposes of comparing the various gas-transport systems, we will adopt as heat source the combustion of hydrogen or methane with oxygen carried in a pressure vessel, (a) above. This reaction has the advantages of being comparatively efficient and of lending itself readily to quantitative calculations. Assuming that the heat from this reaction can be utilized with an efficiency of 50 per cent, about 1.1 gm is the mass of O_2 together with its tankage for 1 kcal. Where fuel must be transported in addition to oxidizer, we will assume that ethyl alcohol is used, making a total mass of about 1.5 gm per kcal.

General Remarks

Table 5 suggests that the mass efficiency of cryogenic hydrogen transport is fairly high (greater than 0.1) if the gas transported by this method amounts to 10 kg or more. The volume required is somewhat excessive, however, since insulating material is needed and liquid H_2 has such a low density (0.07). As pointed out, heat must be provided to gasify the liquid and to bring it up to balloon-filling temperature. The apparatus required to accomplish this, although theoretically not particularly complicated, is considerably more elaborate than required for high-pressure gas.

Here again, considerable developmental research is required before a final design can be specified.

GASES CHEMICALLY GENERATED

Only two of the gases we are considering for the Mars balloon can be "chemically generated," i.e., carried to the planet in the form of chemical compounds from which they are then extracted. These are hydrogen, and decomposed ammonia. (The latter consists by volume of three parts of hydrogen to one part of nitrogen, and is produced when ammonia, whose transport we discussed in the last section, is decomposed catalytically.)

Hydrogen can be carried "condensed" in certain hydrogenous compounds from which it can be extracted. Suitable compounds or reactions should be characterized by: chemical stability, a large mass fraction of hydrogen generated, and a simple, easily controlled release of the bound hydrogen.

The problem of hydrogen's chemical transport merits detailed experimental study. We were limited to selecting from the chemical literature those compounds and reactions that appeared promising. It should be stressed that nearly all of the reactions mentioned are untested, in that they have never been used for hydrogen generation outside the laboratory. We have not been able to consider at all the very important problem of how to achieve a lightweight, reliable gas-generation system that will allow whatever reaction is chosen to proceed at the rate necessary for balloon filling. Such practical considerations are central to the design of a gas-generation system.

For a chemical system, the mass efficiency of the transport system is

$$\frac{m_g}{m_t} = \frac{m_g}{m_c f_h + m_Q} ,$$

where m_c is the total mass of chemicals, f_h is a factor to allow for container and other masses that are proportional to the quantity of chemicals carried, and m_Q is the mass of any heat source necessary to create the reaction. We assume that there are no losses during the space flight.

Two kinds of reactions could be used: a hydrogenous compound decomposing in the presence of heat and catalysts, and two compounds interacting (as in hydrolysis) to produce hydrogen. The more interesting are those that involve compounds containing a large mass fraction of hydrogen -- particularly the hydrogenous compounds of the light elements Li, Be, B, C, N, O. Thermal decomposition has the better potential efficiency because hydrolysis generally creates for its end product a hydrogenous precipitate, thus "losing" some of the hydrogen. It is also usually difficult to make the reaction go to completion. Finally, we would have to transport <u>both</u> the hydride and the water to the planet;* the reaction could not be carried out with an excess of water, as is common practice on Earth where water is "free."

The most interesting <u>lithium</u> compounds seem to be the hydride LiH, the borohydride $LiBH_4$, and lithium aluminum hydride $LiAlH_4$ (an unusual compound). The hydride is thermally stable even beyond its melting point (650°C),[B.8] while the borohydride decomposes slowly at temperatures around 275°C, releasing about half its bound hydrogen.[B.9] $LiAlH_4$ decomposes upon heating (125°C) to LiH, Al, and H_2.[B.10] The hydride, LiH, reacts vigorously with water, liberating hydrogen and leaving the hydroxide LiOH, which is thermally stable even higher than 450°C.[B.8] The reaction of $LiBH_4$ with water is complicated: a small amount of water reacts very vigorously with an excess of $LiBH_4$ to produce diborane, while $LiBH_4$ dissolves in an excess of water at 0°C without further reaction.[B.11] At 100°C, about half of the hydrogen is liberated from the aqueous solution; it appears that certain catalysts (notably $NiCl_2$) enhance the hydrolysis reaction. The "exotic" compound, $LiAlH_4$, has the unusual property of reacting with ammonia to produce hydrogen according to the following formula:[B.12]

---

*The possibility of extracting useful quantities of water from the atmosphere or surface minerals, while not excluded, appears remote.

$$2LiAlH_4 + 5NH_3 \rightarrow [LiAlH(NH_2)_2]_2\,NH + 6H_2 \ .$$

Beryllium compounds have been much less extensively studied than those of lithium. The hydride, BeH_2, is very difficult to prepare, and its properties are dependent on impurities in the final product;[B.13,B.14] BeH_2 of 80 per cent purity (by weight) decomposes at 200°-220°C;[B.14] the pure substance, if it can be prepared, probably decomposes at a somewhat higher temperature. No information could be found about the long-term stability of the compound. It reacts with pure water only slowly, although hydrogen is readily evolved from acidic solutions; the presence of an ether impurity appears to greatly enhance the hydrolysis reaction.[B.14,B.15] Beryllium borohydride, $Be(BH_4)_2$, reacts vigorously with water.[B.16] (It should be noted that a serious disadvantage of beryllium compounds as hydrogen gasogenes is that if the hydrogen-generation reaction goes to completion, the end product is colloidal beryllium, a very toxic substance. This property could make a gas-generation system using beryllium compounds difficult to develop and test adequately and safely on Earth.)

Boron forms a great number of hydrides; the one with the greatest mass fraction of hydrogen is diborane, B_2H_6. Diborane is a poisonous, corrosive gas that is unstable and difficult to liquify and to handle. It reacts violently with liquid water* to form hydrogen and boric acid.[B.17] Boric acid (H_3BO_3) could, in principle, be subsequently dehydrated by heat and reduced pressure.[B.19] Most other hydrides of boron are unstable and offer handling and storage problems; the only exceptions are those with very high molecular weights, which however, contain a low hydrogen fraction. Boron hydrides appear to present too many technical problems to be interesting for the present application. Even so, a more thorough examination of the gas-transport problem should certainly include a reexamination of these compounds.

---

*Diborane reacts more tractably with water vapor and with ice.[B.18]

The most interesting carbon compound for the present application is methane, CH_4, which contains 25 per cent hydrogen by mass. We have already discussed methods for transporting methane to Mars. On Earth an important commercial source of hydrogen is the "water-gas" reaction of methane and superheated steam. This reaction is unsuited for the present application because the products must be washed with water to remove the generated CO_2. Methane alone can be decomposed at high temperatures in the presence of catalysts.[B.20] (Useful catalysts are Ni, Fe.) Since carbon is the solid end-product, the reaction rate is eventually governed by the equilibrium in the system $C-CH_4-H_2$.[B.21] High temperatures (~ 1000°C) are required for effective dehydrogenation. It is always possible that a more convenient way could be devised for catalytically decomposing methane -- it might then be an interesting source for hydrogen. A drawback, of course, is that it is gaseous at ordinary temperatures and for efficient transport must be carried as a liquid at reduced temperatures.

For our purpose, the only important nitrogen compound is ammonia, NH_3. Its transport to Mars as a liquid has already been discussed in the previous section of this appendix. It is decomposed at high temperatures in the presence of many metals and metal oxide catalysts. As an example, ruthenium can be used at a temperature of about 450°C -- the heat of the reaction is about 2 kcal/gm.[B.22] Since two gases are thus produced, a further step is required to separate the hydrogen from the nitrogen. This can be achieved by allowing the hydrogen to diffuse through heated palladium.[B.23] Unfortunately, the diffusion rate is slow, and heating the palladium requires a further expenditure of power. A possible alternative is to omit this final step and use the resulting gas mixture, $1/4(N_2+H_2)$, as a balloon gas.[B.24] This gas has an effective molecular weight of 8.5, half that of ammonia, and has been included in our analysis under the name "decomposed ammonia." Hydrogen generation by the direct reaction of NH_3 and $LiAlH_4$ has already been mentioned.

To complete the list, the only interesting oxygen compound is water, H_2O, which can be made by hydrolysis to give up part of its hydrogen, as previously discussed. The other possibility, electrolysis, is slow and inefficient.

Table 6 lists these various hydrogenous compounds with their hydrogen mass fraction, and possible hydrogen-generating reactions.

For computational purposes, we have chosen the simple thermal decomposition reaction of beryllium hydride. As already mentioned, this reaction is uncertain; published information is scanty and somewhat contradictory. However, it appears very promising and merits thorough investigation. Assuming that the necessary heat can be generated from the reaction of BeH_2, water, and catalysts, we estimate the following ratios for this gasogene:

$$m_g/m_t = 0.09$$

and

$$V_t/m_g = 15 \quad .$$

These estimates contain a small allowance for auxiliary equipment, such as reaction vessels and metering valves. Clearly, the success of the gas-generation system greatly depends on the development of reliable, very lightweight equipment that will generate the required gas at a rate suitable for filling balloons.

Table 6

HYDROGEN GASOGENES

Compound	Hydrogen Mass Fraction	Examples of Hydrogen-Generating Reactions	Refs.
LiH	0.126	$LiH+H_2O \rightarrow LiOH+H_2$ (exothermic)	
$LiBH_4$	0.184	$LiBH_4+2H_2O \xrightarrow[100^{\circ}C]{} LiBH_2(OH)_2+2H_2$	B.11
$LiAlH_4$	0.105	$2LiAlH_4 \xrightarrow[125^{\circ}C]{} 2LiH+2Al+3H_2$ (follow by hydrolysis of LiH)	B.10
BeH_2	0.181	$BeH_2 \xrightarrow[250^{\circ}C(?)]{} Be+H_2$ (lower temperatures through catalysts?)	B.12 B.13 B.14
		$BeH_2+2H_2O \rightarrow Be(OH)_2+H_2$ (exothermic if catalyzed or in acidic solution)	
$Be(BH_4)_2$	0.208	$Be(BH_4)_2+8H_2O \xrightarrow[\text{violent}]{} Be[B(OH)_4]_2+8H_2$	B.15
B_2H_6	0.226	$B_2H_6+6H_2O(\text{liquid}) \xrightarrow[\text{violent}]{} 2H_3BO_3+6H_2$ (follow by dehydration of H_3BO_3 to B_2O_3)	B.16 B.19
CH_4	0.250	$CH_4 \xrightarrow[\sim 1000^{\circ}C]{} C+2H_2$ (Fe or Ni catalyst)	B.18 B.20
NH_3	0.176	$2NH_3 \xrightarrow[\sim 450^{\circ}C \text{ catalyst}]{} N_2+3H_2$ (to separate H_2, use Pd diffusion tubes)	B.21 B.22
H_2O	0.111	$2H_2O \rightarrow O_2+2H_2$ (electrolysis)	

CONCLUDING REMARKS

Though chemical methods appear more efficient in both mass and volume, our present knowledge and experience make them uncertain. For a kilogram or more of hydrogen, cryogenic transport is efficient in mass, but less so for volume. And though high-pressure transport is considerably less complicated than chemical and cryogenic methods, it is relatively inefficient and uncertain technically.

The present study has not resolved the problem of gas transport, but it has suggested a number of possible alternative approaches. Hopefully, one or more of them will prove to be an adequate solution after development.

REFERENCES FOR APPENDIX B

B.1 Roark, R. J., Formulas for Stress and Strain, McGraw-Hill Book Company, New York, 1954.

B.2 Hoffman, G. A., private communication.

B.3 Walker, R. G., Infrared Celestial Backgrounds, Air Force Cambridge Research Laboratories, AFCRL-62-807, July 1962.

B.4 Vance, R. W., and W. M. Duke (eds.), Applied Cryogenic Engineering, John Wiley and Sons, New York, 1962.

B.5 Scott, R. B., Cryogenic Engineering, D. Van Nostrand and Company, Princeton, 1959.

B.6 Mellor, J. W., A Comprehensive Treatise on Inorganic and Theoretical Chemistry, Longmans, Green and Company, London, 1946.

B.7 Stettbacher, A., "Heat Generated by Incendiary Bombs and the Danger of Suffocation Because of Fixation of Atmospheric Oxygen," Protar, Vol. 10, 1944, pp. 158-164.

B.8 Handbook of Chemistry and Physics, 30th ed., Chemical Rubber Publishing Company, Cleveland, Ohio, 1947.

B.9 Schlesinger, H. I., and H. C. Brown, "Metallo Borohydrides. III. Lithium Borohydride," J. Amer. Chem. Soc., Vol. 62, 1940, pp. 3429-3435.

B.10 Wiberg, E., "Neuere Ergebnisse der präparativen Hydrid-Forschung," Angew. Chem., Vol. 65, No. 1, 1953, pp. 16-32.

B.11 Mikheeva, V. I., and E. M. Fedneva, "Hydrolysis of Lithium Borohydride," Doklady Akad. Nauk. SSSR, Vol. 101, 1955, pp. 99-101; see Chem. Abs., Vol. 49, Col. 101093, 1955.

B.12 Finholt, A. E., A. C. Bond, Jr., and H. I. Schlesinger, "Lithium Aluminum Hydride, Aluminum Hydride, and Lithium Gallium Hydride, and Some of Their Applications in Organic and Inorganic Chemistry." J. Amer. Chem. Soc., Vol. 69, 1947, pp. 1199-1203.

B.13 Coates, G. E., and F. Glockling, "Di-tert.-butylberyllium and Beryllium Hydride," J. Chem. Soc. (London), Vol. 1954, 1954, pp. 2526-2529.

B.14 Head, E. L., C. E. Holly, Jr., and S. W. Rabideau, "Di-t-butylberyllium and Beryllium Hydride," J. Amer. Chem. Soc., Vol. 79, No. 14, 1957, pp. 3687-3689.

B.15 Schlesinger, H. I., *et al.*, "Sodium Borohydride, Its Hydrolysis and Its Use as a Reducing Agent and in the Generation of Hydrogen," *J. Amer. Chem. Soc.*, Vol. 75, No. 1, 1953, pp. 215-219.

B.16 Burg, A. B., and H. I. Schlesinger, "Metallo Borohydrides. II. Beryllium Borohydride," *J. Amer. Chem. Soc.*, Vol. 62, 1940, pp. 3425-3429.

B.17 Gunn, S. R., and L. G. Green, "The Heats of Hydrolysis of Diborane and Boron Trichloride," *J. Phys. Chem.*, Vol. 64, 1960, pp. 61-63.

B.18 Urusov, V. V., "Thermographic Study of the Process of Dehydration of Orthoboric Acid," *Doklady Akad. Nauk. SSSR*, Vol. 116, 1957, pp. 97-100; see *Chem. Abs.*, Vol. 52, Col. 5187c, 1958.

B.19 Weiss, H. G., and I. Shapiro, "Mechanism of the Hydrolysis of Diborane in the Vapor Phase," *J. Amer. Chem. Soc.*, Vol. 75, No. 5, 1953, pp. 1221-1224.

B.20 Spektor, B. V., "Deep Thermal Decomposition of Methane," *Zhur. Priklad. Khim.*, Vol. 29, 1956, pp. 1078-1082; see *Chem. Abs.*, Vol. 50, Col. 17376d, 1956.

B.21 Browning, L. C., and P. H. Emmett, "Equilibrium Measurements in the System $C-CH_4-H_2$," *J. Amer. Chem. Soc.*, Vol. 73, No. 2, 1951, pp. 581-583.

B.22 Amano, Akiro, and H. Taylor, "The Decomposition of Ammonia on Ruthenium, Rhodium, and Palladium Catalysts," *J. Amer. Chem. Soc.*, Vol. 76, No. 16, 1954, pp. 4201-4204.

B.23 *Handbook of Operating and Maintenance Instructions for Generator, Hydrogen ML-539 (XD-2)/TM Type II*, Engelhard Industries, Inc., Chemical Division, Gas Equipment Department, Newark, New Jersey, March 1960.

B.24 Darling, A. S., "The Diffusion of Hydrogen through Palladium," *Platinum Metals Rev.*, Vol. 2, 1958, pp. 16-22.

Appendix C

THE RATE OF RISE OF A BALLOON AND THE PARAMETER LAMBDA

In this appendix we shall examine the equations of motion of a balloon rising through a still atmosphere for the restricted case of the balloon gas and the ambient temperatures being essentially equal at all times. In addition, we shall examine the quantitative limits that might be placed on the parameter λ, and suggest a single reasonable value of this parameter to use in this study.

THE MOTION OF THE RISING BALLOON

The conditions under which the balloon will ascend and the amount of gas required for a specified upward acceleration have been established. Now the behavior of the balloon as it rises can — at least approximately — be described.

Following the usual practice, we may write

$$F_D = C_D A(\tfrac{1}{2}\rho v^2),$$

where A is the cross-sectional area of the balloon, v is its vertical velocity relative to the air, and C_D is the drag coefficient. The drag coefficient is a function of the Reynolds number, which is itself a function of the density and viscosity of the medium, the velocity of the body through the medium, and a length characteristic of the body. A graphical relationship of C_D to Reynolds number for two body configurations is presented in Fig. 11.[C.1] For balloons flown in Earth's atmosphere, the Reynolds number is in the range 10^3 to 10^6, which (if a balloon is assumed to be a sphere) would suggest a C_D of about 0.5. However, experience with plastic balloons has indicated[C.2] that although C_D undoubtedly changes with altitude because of the expansion of the gas and the resulting change of balloon shape, we may still with reasonable accuracy assume a constant C_D. A good approximation for C_D is 1, which is very close to that for a flat disk of equal cross-sectional area (see Fig. 11) moving in a direction normal to its plane. That the empirically determined drag coefficient differs to this degree from the coefficient calculated for

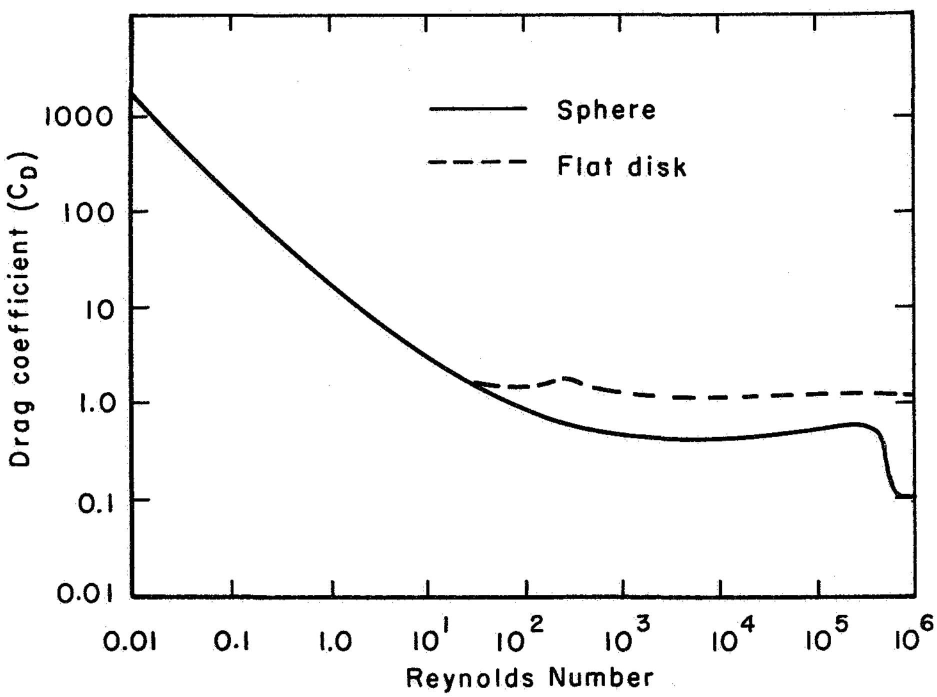

Fig. 11 — Relationship of drag coefficient to Reynolds number, shown for a sphere and for a flat disk of same radius (after Ref. C. 1)

a sphere is evidence that an ascending, partially filled balloon cannot be considered to approximate a sphere hydrodynamically. Even extensible balloons, although filled and approximately spherical when launched, are not rigid, and hence, undergo some deformation during the ascent, making the drag coefficient higher than for a sphere. There is some indication[C.3] that the drag coefficient, at least for small extensible balloons, is about 0.8 for Reynolds numbers of about 10^4—10^5.

Returning to Eq. (2.2), we may now write

$$F_T = F_B - \tfrac{1}{2}C_D\rho v^2 A = m^*a, \qquad \text{(C.1)}$$

or

$$a = \frac{F_B}{m^*} - \frac{1}{2m^*}C_D v^2 A.$$

As the balloon ascent begins with $v = 0$, $a = a_0$, then

$$a_0 = \frac{F_B}{m^*} \quad . \qquad \text{(C.2)}$$

It would be highly desirable to derive a complete analytical solution to Eq. (C.1). But in a complicated atmosphere, such a solution is, in effect, impossible to obtain. Of course, in an atmosphere for which the temperature structure is well known (even though not expressible as a complete analytical function), numerical solutions are possible, if the variation of a balloon's gas temperature with altitude is also known.* Although it might be suspected that the gas temperature would vary adiabatically as the balloon rises, eventually it must depart from the simple adiabatic variation as it attempts to come into thermal equilibrium with the various sources of heat which affect it. (See Appendix A.)

---

*The gas temperature enters Eq. (C.1) as was shown in Eq. (2.5) by the ratio of gas temperature to ambient temperature. In addition, the cross-sectional area, A, is a function of balloon temperature; therefore Eq. (C.1) involves T' in a complicated way.

Assume that the temperatures of the air and gas vary adiabatically with altitude and with the same lapse rate (very nearly the case for a hydrogen-filled balloon in a nitrogen atmosphere; see Appendix A); then, to a first-order approximation, β remains constant with altitude. Under these assumptions, an analytical solution to Eq. (C.1) can be found as follows:

Assuming that the balloon may be considered a rigid sphere when discussing the drag forces affecting it, A may then be expressed in terms of the balloon volume as

$$A = \sqrt[3]{36\pi}\ V^{2/3}$$

and

$$V = \frac{m_g}{\rho}\left(\frac{\rho}{\rho'}\right) .$$

Approximate the density variation of the air and gas with altitude z as,

$$\rho = \rho_0\ e^{-z/H_a}$$

and

$$\rho' = \rho_0'\ e^{-z/H_g} , \tag{C.3}$$

where H_a and H_g are the "effective scale heights" of the air and gas.*
Then

$$V = \frac{m_g}{\rho}\left(\frac{\rho_0}{\rho_0'}\right)\ \exp\left[-z\left(\frac{1}{H_a} - \frac{1}{H_g}\right)\right] .$$

Writing

$$\frac{1}{2}\ C_D\left(\frac{\rho v^2}{m^*}\right)A \text{ as } D\left(\frac{v^2}{2}\right)e^{-\alpha z} ,$$

where

$$D = \frac{4.8\ C_D}{m^*}\ \rho_0\left(\frac{m_g}{\rho_0'}\right)^{2/3} ,$$

---

*Eqs. (C.3) should be regarded as fits to the actual variation of ρ and ρ' with altitude. The variation of density with altitude is well approximated by an exponential function for an adiabatic atmosphere.

and

$$\alpha = \left[\frac{1}{H_a} - \frac{2}{3H_g}\right].$$

Since

$$a = \frac{dv}{dt} = v\frac{dv}{dz} ,$$

if we make the substitution

$$v^2 = u,$$

then Eq. (C.1) may be written as

$$\frac{du}{dz} = B - u\,De^{-\alpha z} , \tag{C.4}$$

where

$$B = \frac{2F_B}{m^*} .$$

Noting that α is a small quantity, we may approximate $e^{-\alpha z}$ as,

$$e^{-\alpha z} \approx 1 - \alpha z \approx \frac{1}{1+\alpha z} .$$

Eq. (C.4), therefore, becomes

$$\frac{du}{dz} = B - \frac{Du}{1+\alpha z} . \tag{C.5}$$

Eq. (C.5) may be solved to yield

$$v^2 = \frac{B}{D+\alpha}\left[1+\alpha z - \frac{1}{(1+\alpha z)^{D/\alpha}}\right] . \tag{C.6}$$

Differentiating Eq. (C.6) to obtain the acceleration we have

$$a = \frac{B}{2(D+\alpha)}\left[\alpha + \frac{D}{(1+\alpha z)^{(D/\alpha)+1}}\right] . \tag{C.7}$$

Remembering that $B = 2F_B/m^*$, and from Eq. (2.1), $F_B = a_0 m^*$, where a_0 is the initial acceleration of the balloon, then

$$a = \frac{a_0}{D+\alpha} \left[\alpha + \frac{D}{(1+\alpha z)^{(D/\alpha)+1}} \right] . \tag{C.8}$$

If the proper substitutions are made, then we may write

$$D = \frac{A_0 C_D \rho_0}{m^*} ,$$

and

$$\alpha = \frac{1}{3H_a} [3 - 2/\beta] ;$$

since $\beta > 1$, and using the equation of state and the definition of scale height,

$$\frac{D}{\alpha} \approx \frac{A_0 P_0 C_D}{m^* g} , \qquad \text{and } \alpha \approx \frac{1}{H_a} . \tag{C.9}$$

$A_0 P_0$ is the force of the atmosphere on a balloon sitting on the surface and is equal to the mass of the air, m_a, in the total atmospheric column of cross-section A_0 multiplied by g. For a balloon in dynamic equilibrium on the surface, [Eq. (2.1), $F_B = 0$; $m^* = m$], m^* is equal to the mass of air, m_v, displaced by a balloon volume, V_0.

Therefore

$$\frac{D}{\alpha} \approx \frac{m_a}{m_v} C_D ;$$

since even for a rather thin atmosphere $m_a/m_v > 1$, then, $D/\alpha \gg 1$, and $D \gg \alpha$. Hence except when the balloon is very near the surface, we may neglect the term $1/(1+\alpha z)^{D/\alpha}$ in Eq. (C.6). Under these conditions the velocity may be expressed as

$$v = \sqrt{\frac{2a_0 m^*}{A_0 C_D \rho_0} (1+\alpha z)} \tag{C.10}$$

and the acceleration as

$$a = \frac{a_0 m^*}{A_0 \rho_0 C_D} \alpha \ . \tag{C.11}$$

In essence then, the balloon has an initial acceleration, a_0, which the drag force of the air degrades to a value of a, and from that point on the balloon acceleration remains constant until a condition of equilibrium is reached ($F = 0$), or the balloon bursts. To determine the degree to which Eq. (C.11) may be applied to the general motion of a balloon, it is necessary to determine how early in its rise it achieves the condition of constant acceleration. For D/α large and αz small (i.e., z less than a scale height H_a) Eq. (C.7) may be rewritten to yield

$$\frac{a}{a_0} \approx \left(1 - \frac{\alpha}{D}\right) e^{-Dz} + \frac{\alpha}{D} \ . \tag{C.12}$$

Equation (C.12) may be solved for z in the restricted case of $z \neq 0$,

$$z = \frac{1}{\alpha}\left(\frac{\alpha}{D}\right) \ln\left(\frac{\alpha}{D} - \frac{a}{a_0}\right) \ . \tag{C.13}$$

If, for Mars,* we assume $\alpha/D = 10^{-3}$, and ask at what altitude does $a/a_0 = 1.01\ \alpha/D$, we find that this condition occurs at $z = 10^{-2} H_a$. In other words, the acceleration is within <u>one per cent</u> of its constant value by the time the balloon has reached an altitude equal to <u>one per cent</u> of the Martian scale height. This very small constant acceleration implies an almost constant velocity. In proof of this, it is very easy to show that Eq. (C.10) is essentially equivalent to the terminal velocity obtained by setting Eq. (C.1) equal to zero and solving v with

$$v = \sqrt{2F_B/\rho C_D A}$$

---

*$D/\alpha = A_0 P_0 C_D / m^* g$; on Mars P_0 is of the order of 10^5 gm-cm/sec^2, and g is of the order of 4×10^2 cm/sec^2; m^* should be of the order of 2×10^4 gm and A_0, the initial balloon cross section, of the order of 3×10^4 cm^2, then assuming $C_D \approx 1$ we have $D/\alpha \approx 10^{-3}$.

The assumptions used to obtain a solution to Eq. (C.1) appear sound enough to warrant the statement that Eq. (C.10) provides a good first-order approximation to the vertical velocity of a balloon in the Martian atmosphere. It also appears that this approximation is good up to an altitude where atmospheric temperature no longer varies adiabatically (a planetary tropopause) or to an altitude equal to about one planetary scale height — whichever occurs first.

THE PARAMETER λ

Because of the interdependence of the various balloon parameters and the fact that the λ enters implicitly into almost all of the various performance equations, in practice one would choose a value of λ and then evaluate a specific system with this parameter now considered a constant. It is important, therefore, to determine the possible limits on λ to guide us in making a reasonable choice. The first limit that we might examine is that which provides us with a minimum value of λ. From Eq. (2.13) it is obvious that if we can state a minimum velocity, we can, in effect, determine a corresponding minimum value of λ. The criterion for a minimum velocity is actually quite simple. We desire that the balloon ascend fast enough (under the additional influence of horizontal air motion) to clear any natural hazard. With our present lack of knowledge on Martian terrain characteristics, and our present uncertainty in surface wind velocities, it is rather difficult to estimate the desired ascent angle with any degree of confidence. Yet it is important to make such an estimate (recognizing the attendant uncertainties) since, if possible, we wish to avoid decreasing the general efficiency of the system by requiring it to achieve a higher vertical velocity than is necessary to accomplish its mission. One approach in estimating the required angle of ascent is to assume a reasonable value for the natural angle of repose of the surface materials. If, as presently appears reasonable, we may assume that the bright areas on Mars are a form of sandy desert, then a possible angle of repose might be the known angle for sandy materials on Earth as modified for the conditions on Mars. The angle of repose for sandy materials on Earth is approximately 30° (measured from the horizontal). The low water-vapor content of the Martian atmosphere will tend to decrease this angle, while lower gravity will tend to increase it. These two effects may cancel one another. Although the angle of repose is a nice concept in theory, in practice as can be seen from the terrain on Earth, there are many departures from such an idealized model. To take a conservative viewpoint we shall assume a desired minimum angle of rise for the balloon on Mars to be 40^o. While such an assumption will not take care of the case of a balloon launched at the base of a steep escarpment, it also does not assume the possibly unrealistic condition of all of Mars consisting of gently rolling countryside. An estimate of a possible upper limit on horizontal wind may be obtained by an examination of the available observations of cloud motions on Mars (Chapter III). These observations indicate that while the initial velocities of these clouds are of the order of 50—90 km/hr, their velocity at the time of their disappearance is of the order 10 km/hr (3 m/sec). Without arguing the point of the altitude at which these winds occur, it is clear that 3 m/sec probably is a velocity at storm abatement, and as such, might be assumed to be an estimate of the nonstorm wind velocity on Mars. Assuming then a wind velocity of 3 m/sec, and an ascent angle of 40^o, we obtain an estimate of the minimum desired vertical velocity of approximately 250 cm/sec.

Starting with Eq. (C.10) and assuming $z \approx 0$ we have

$$(m_g[\beta - 1] - m_L)g = (C_D v^2 \rho_0 A_0)/2 \quad . \qquad \text{(C.14)}$$

Defining A_0 in terms of the initial radius of the balloon and the initial radius in terms of the mass of the gas, it is possible to remove the dependence on the balloon geometry, therefore yielding an expression for m_p as,

$$m_p = \left[\beta\left(\frac{1-\lambda/2}{\lambda + 1}\right) - 1\right] \frac{m_p}{m_L} \left[\frac{C_D v^2 (\lambda+1)}{4\lambda g}\right]^3 \frac{4\pi\rho_0}{3\beta} \, . \qquad \text{(C.15)}$$

Utilizing Eq. (2.18) expressing the relationship between m_p/m_L and m_p, it is possible to obtain the following expression for

$$m_p = \frac{4\pi}{3} \rho_0 \frac{\beta(1 - \lambda/2)/(\lambda + 1) - 1}{\beta} \left[\frac{C_D v^2(\lambda + 1)}{4g\lambda}\right]^3 -$$

$$- 4\pi t_b \rho_b (\rho_0/\rho_m)^{2/3} \left[\frac{C_D v^2(\lambda + 1)}{4g\lambda}\right]^2 , \qquad \text{(C.16)}$$

where t_b and ρ_b are the thickness and density of the balloon materials respectively, and ρ_m is the density at the floating altitude.* Assuming from Chapter VI a value of 1.92×10^{-3} for $t_b \rho_b$, 5×10^{-5} for ρ_m, 10^{-4} for ρ_0, 3.9×10^2 for g, and 1 for C_D, we may plot a curve of λ_{min} versus payload mass for a minimum value of velocity equal to 250 cm/sec. Such a plot is presented in Fig. 12 for the case of hydrogen ($\beta_0 = M_a/M_g = 14.5$), and decomposed ammonia (β_0 equal to 3.41). As can be seen from this figure, while there is certainly not a constant value of λ_{min} that can be assumed, it appears that a λ equal to 0.1 is adequate for payloads greater than 10 kg. To examine the velocity implications of choosing a λ equal to 0.1, we may plot payload versus velocity for this constant value of λ. These curves are presented in Fig. 13. From this figure it is apparent that with the uncertainties attendant on our choice of v_{min}, a value of λ equal to 0.1 is reasonable.

Before accepting this value, however, we must ask whether the λ_{min} chosen exceeds the maximum limit that might be placed on λ with a somewhat different set of criteria. As stated previously, the drag coefficient for a balloon is greater than for a sphere, and in the case of the large plastic balloon, approaches that for a flat disk moving normal to its plane. It is very difficult to determine what might be a limiting Reynolds number for safe, reliable operation of such thin-skinned vehicles. We do know, however, that balloons

*For an extensible balloon, ρ_m would be replaced by ρ_f, the bursting altitude, and the extreme right-hand term in Eq. (C.16) would be divided by approximately 1.3.

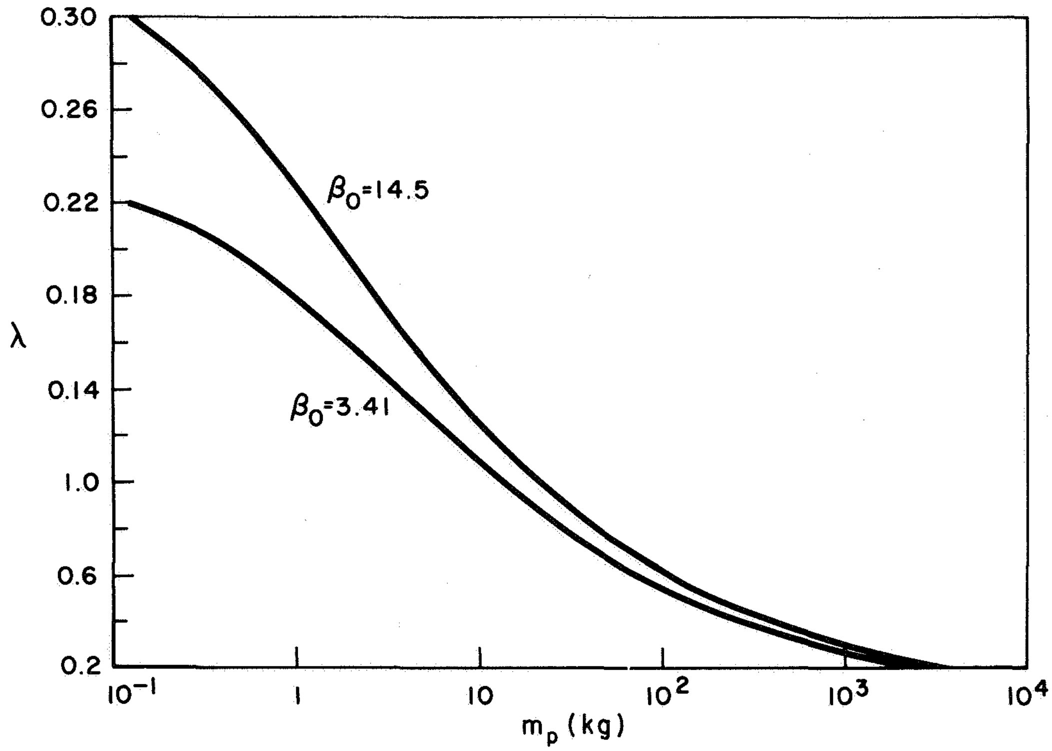

Fig. 12 — The parameter lambda versus payload mass for two values of β_0: hydrogen and decomposed ammonia (v assumed to be 250 cm/sec)

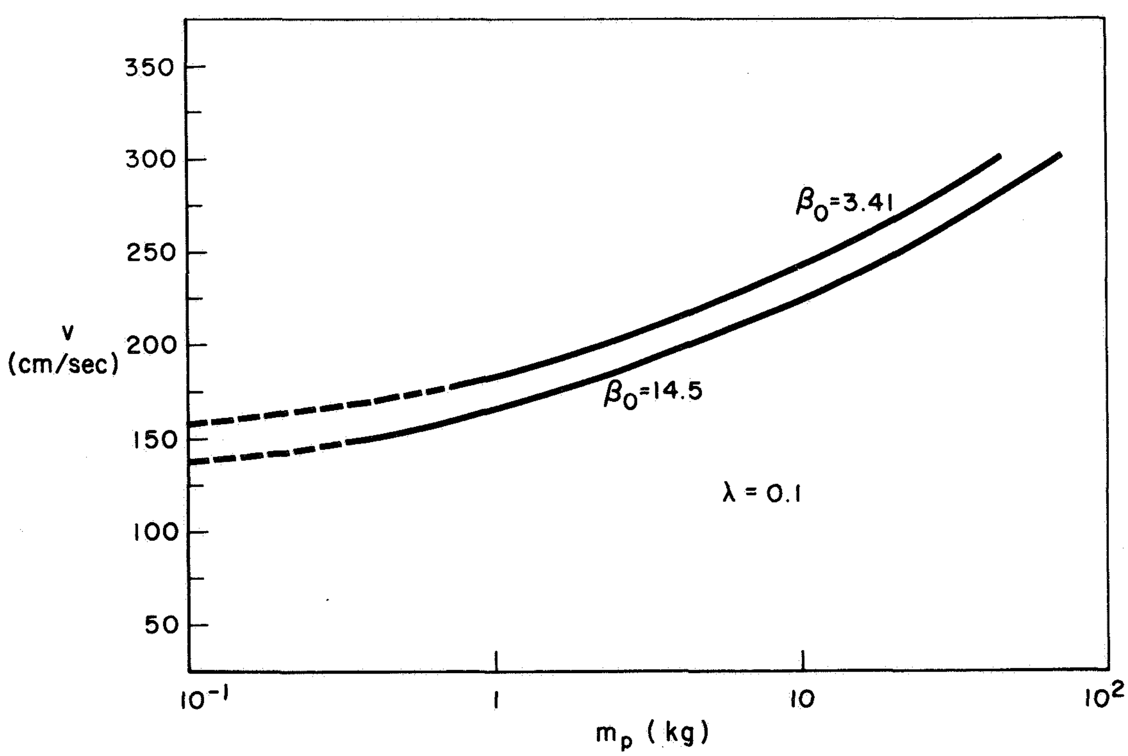

Fig. 13 — Balloon velocity versus payload for hydrogen and decomposed ammonia

in Earth's atmosphere have operated reliably with Reynolds numbers of the order of 10^6. Without making a judgment as to whether or not a balloon could be built that would operate reliably at significantly higher Reynolds numbers, we shall assume, perhaps conservatively, that Re = 10^6 will be the maximum value permitted. As in the case of λ_{min}, we may start with Eq. (C.10), defining A_0 in terms of the balloon radius, and solve for r_0. Utilizing the formal definition for Reynolds number, namely,

$$Re = 2\rho_0 r_0/\eta \quad ,$$

where η is the viscosity of the air [for a nitrogen atmosphere $\eta = 1.38 \times 10^{-5} T^{3/2}/(T + 103)$ gm cm^{-1} sec^{-1}], we may remove the dependence on balloon radius, yielding

$$m_p = \frac{\pi C_D (Re)^2 \eta^2}{12 g \rho_0 \beta_0 \lambda} \left(\frac{m_p}{m_L} \right) \left(\beta \frac{1 - \lambda/2}{\lambda + 1} - 1 \right) (\lambda + 1) \quad . \qquad \text{(C.17)}$$

Utilizing once again the relationship between m_p/m_L and m_p, given by Eq. (2.18), we may obtain the following expression for m_p:

$$m_p = \frac{\pi}{12} \left\{ \frac{\beta\left(\frac{1-\lambda/2}{\lambda+1}\right) - 1}{\beta} \; \frac{(\lambda + 1)}{\lambda} \; \frac{C_D (Re)^2 \eta^2}{\rho_0 g} - \frac{7.56 t_b \rho_b}{\rho_m^{2/3}} \left[\frac{(\lambda + 1)}{\lambda} \; \frac{C_D (Re)^2 \eta^2}{\rho_0 g} \right]^{2/3} \right\} . \qquad \text{(C.18)}$$

Assuming the same parameter values as in the case of λ_{min}, and substituting-in the assumed maximum value of Reynolds number, Eq. (C.17) may be solved for payload mass as a function of λ_{max}. If we now assume λ_{max} to be equal to 0.1, this equation yields a value of m_p equal to 1.4×10^3 kg for hydrogen, and 0.54×10^3 kg for cracked ammonia. It is apparent, then, within the limits of uncertainty of our assumptions, that λ equal to 0.1 appears to be a reasonable choice for payloads up to approximately 10^3 kg.

REFERENCES FOR APPENDIX C

C.1 Encyclopaedic Dictionary of Physics, Vol. 6, Section on "Reynolds Number," Pergamon Press, Oxford, 1962.

C.2 University of Minnesota Physics Department, Reports on Research and Development in the Field of High Altitude Plastic Balloons, Contract NONR-710(01), DDC No. AD-75998.

C.3 Handbuch der Experimentalphysik, Vol. 4, Part II, Hydro- und Aerodynamik, Widerstand und Auftrieb, Akademische Verlagsgesellschaft, M.B.H., Leipzig, 1932.